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Study on Rutting Behaviour of Waste Steel Fibre Asphalt Mixture

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ABSTRACT

This study discusses on studies on the use and effectiveness of waste steel fibre as an additive in modifying asphalt mixture to enhance rutting resistance. The objectives were to evaluate the influence of incorporating steel fibre on rutting behaviour by measuring the index of retained strength. Various amounts of steel fibre (0%, 1%, 2%, and 3%) were added to the asphalt mixture using the Superpave mix design method. Determining the optimum bitumen content resulted in identifying 5.5% bitumen content, which exhibited desirable performance characteristics. Performance tests were conducted to assess the impact of including steel fibre on rutting resistance and permanent deformation. Surprisingly, the results indicated that slightly including steel fibre improves rutting resistance or reduces permanent deformation. These findings suggest that adding waste steel fibre within the tested percentages can slightly enhance the rutting resistance or mitigate permanent deformation in the asphalt mixture. Further research and exploration are required to identify alternative approaches for improving the rutting resistance of asphalt mixtures.

1. Introduction

The significant expansion of Malaysia's national infrastructure network over the previous decade has increased road building. With 87,626 km, asphaltic roads dominate the overall surfacing types. Many transportation operations take place on roads and highways across the world [1]. The asphalt mixture's components (bitumen and aggregate) are considered sensitive materials, particularly temperature and frequent stress, which might diminish the pavement's service life [2]. Although these pavements are still in service, much money is allocated for maintenance work annually due to pavement distress, which sometimes occurs prematurely due to increasing traffic loads and wet tropical climatic conditions [1].

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Flexible pavements are designed to have a lifespan of at least 20 years, and the goal of asphalt pavement design is to calculate the thickness of the pavement layers necessary to sustain repeated loads safely under environmental circumstances without considerable deformation based on the qualities of the materials used in asphalt pavement layers [3]. Current research includes studies on improving off-road pavements' performance and longevity. Various additive materials are used to enhance the performance and lifespan of roadways [4]. The increased stiffness improves the rutting resistance of the asphalt pavement in high-temperature conditions and allows for the use of more flexible asphalt [3]. To overcome any potential consequences, the pavement must be enhanced with additives. Fibres are one of the additions utilised for this purpose [2]. This study systematically investigated the fibre content as a critical parameter that significantly affects the performance of fibre-reinforced asphalt mixtures. The objectives were to evaluate the influence of incorporating steel fibre on rutting behaviour by measuring the index of retained strength. Concerning assessing the effectiveness of the percentage of steel waste fibre used in the asphalt mixture in terms of its capacity to resist rutting, this study aims to provide researchers with suggestions for subsequent research involving the length of use of steel waste fibre.

1.1 Rutting in Asphalt Pavement

Rutting, a form of structural failure, poses a significant risk to the integrity and performance of asphalt pavements. Rutting was a substantial issue with flexible paving as it acts as one of the primary distresses observed in asphalt pavements, leading to reduced ride quality, safety concerns, and increased maintenance costs. It is a longitudinal dip in the highway wheel tracks categorised as the most prevalent type of pavement permanent deformation caused by recurrent traffic loads accumulating minor endless stresses in pavement materials.

Rutting impact has been a severe regular failure in recent years, paired with a rise in heavy traffic load on roads, particularly in tropical settings. Rutting refers to the longitudinal depressions formed by vehicles moving along their tyre tracks. Rutting is an essential indicator of discomfort for two reasons. If the surface is impermeable, the rut will retain water, creating hydroplaning, a severe potential threat to vehicles. As the rut depth grows, steering becomes increasingly difficult and potentially dangerous. Rutting may significantly impact a pavement's structural and functional performance [6].

Due to increased traffic volumes and vehicle weights, improving the qualities of standard asphalt mixes and their resistance to permanent pavement deformation in the form of ruts or corrugations is critical. Several factors contribute to the rutting resistance of asphalt pavements, and these factors are often considered during the mix design process. Then, of fibres to the asphalt mix can improve rutting resistance by enhancing the mix's tensile strength and resistance to permanent deformation. Engineers may develop asphalt pavements with increased rutting resistance by methodically combining proper mix design and additives, resulting in longer-lasting and more dependable road surfaces.

1.2 Fibre as an Additive in Asphalt Pavement

Using fibres as additives in asphalt pavement is a common practice to enhance the performance and durability of the asphalt mixture [6]. Adding fibres helps improve various mechanical properties and mitigate issues such as cracking, rutting, and fatigue [7]. Asphalt pavement now has stronger tensile resistance thanks to fibres' high modulus, endurance, resistance, and deformation resistance [8]. Additionally, fibres have been utilised to strengthen polymer mixtures employed in subsequent manufacturing processes. These fibres give the strength and rigidity of the composite, enabling the mix to transfer loads across fibres more effectively. Additionally, by enhancing the mixture's characteristics and extending the service life of the road, the inclusion of fibres in asphalt mixes promotes sustainability. Using fibres improves the mechanical performance of asphalt mixture, and fibres reinforce hot mix asphalt through a Tri dimensional network and improve the adhesion in the mix [3].

Different fibres can be used as additives in asphalt pavement, the most common being synthetic fibres and cellulose fibres. Synthetic fibres such as polypropylene, polyester, and recycled fibres give mechanical reinforcement and improve rutting and cracking in asphalt concrete. Most discuss synthetic fibres such as polypropylene polyester recycled fibres [9]. Fibres have been used to reinforce paving materials in most parts of the world for decades. The reinforcement method of using fibres is executed through distribution within the materials or by applying oriented fibrous materials [10].

1.3 Waste Steel Fibre from Waste Tyres used in Asphalt Pavement

A wire is commonly used in various fields such as construction, packaging, and parts manufacturing. Tyre cord steel, specifically, is a type of wire used in radial tires, according to Chen L [7] research. This high-carbon steel wire is commonly used in all commercial and passenger vehicles to reinforce rubber tyres. Steel wires offer higher strength and better riding comfort, which makes them highly desirable in personal cars. Tyres from vehicles disposed of in landfills are one of the most significant components of solid waste. Construction can be completed much more environmentally friendly, and waste tyre steel fibres can be reused in the field of civil engineering by using recycled steel fibres from post-consumer tyres as concrete pavement reinforcement [12,13]. 75% to 90% rubber, 5% to 15% high-strength corded steel wire, and 5% to 20% polymer cloth make up a typical automobile or truck tyre [14]. The waste tyre has been categorised as solid waste and has become a global concern due to the environmental risks associated with its disposal in open areas [15-17].

According to the European Tyre and Rubber Manufacturers Association, approximately 3.5 billion tyres were sold annually globally in 2018 [18] .The simplest and least expensive method of tyre disposal, tyre burning, causes significant problems. When tyres catch fire, extinguishing the flames is extremely difficult and time-consuming, and the resulting ash pollutes the soil. In addition, the hydrocarbon produced when melted rubber pollutes land and water. This scenario entails transferring the issue to a different party, with little possibility of a thorough and lasting resolution. Following Fakhri *et al.*, [19] during the extraction of rubber residue, tyres are reduced to smaller pieces known as crumb rubber . A standard tyre comprises 60% rubber, 20% steel and 20% fibre. This process yields rubber and short steel fibres with many applications. Induction heating was used to test the self-healing and mechanical performance of bituminous mixtures containing reused tyre steel fibres, and it was discovered that these materials increase the self-healing and mechanical properties of the bitumen mixture. The researchers concluded that these fibres pose a safety hazard and therefore should be addressed, it is recommended to be added to the asphalt's binder layer [19]. According to Al-Ridha *et al.,* adding steel fibres to the surface layer of a flexible pavement could cause driver discomfort and reduce road protection, thereby increasing the potential of a tyre puncture [4].

Waste steel fibre can be obtained in various forms, including wool, sticks, and clumps; either the steel fibre is already pure or coated with excess tyre rubber [20,21]. The asphalt mixture containing 6% steel wool fibres has the highest tensile strength, resistance to particle loss, and abrasion resistance [22]. By adding steel fibres to a porous asphalt mixture, Liu *et al.,* stated that this mixture can be heated efficiently via induction heating. They demonstrated that long steel wool with a smaller diameter is more effective at increasing the temperature than short steel wool with a larger diameter [23]. Liu *et al.,* [22] discovered that the fatigue resistance of steel wool-reinforced porous asphalt concrete formulations is greater than the literature norm.

2. Methodology

2.1 Material and Sample Preparation

Fibre as an additive is intended to improve the mechanical performance of the HMA mixture [24]. Waste Steel Fibre (WSF) is the fibre used in this study. The thread was retained by the product of burned tyres [25]. Waste Steel Fibres, WSF were extracted from burned waste tires to assess the impact of using WSF from old waste tires on asphalt pavement. The waste tire steel fibres are 10mm in length. Samples were randomly extracted and analysed based on fibre content.WSF is obtained directly from a used tire extraction factory in Klang, Selangor. The WSF is roughly removed from the used tire without cleaning, so it still contains pieces of tire rubber on the steel fibre. However, the residue of the used tread attached to the fibre is too small to be ignored. According to Augustino *et al.,* [26] most of these are synthetic/industrial fibres economically unviable in the construction industry compared to straight waste tyre steel fibresClick or tap here to enter text. The WSF are prepared to fulfil the properties needed for this study. This fibre is put into hot aggregate with different rates of 0%, 1%, 2%, and 3% by weight of asphalt mixture [14]. Table 1 shows the properties of WSF used in this research. WSF was originally collected from the factory. The physical properties of WSF are commonly used as reinforcement in HMA [24].

Table 1
Physical properties WSF used

Description	Value
Length (mm)	10
Diameter (mm)	0.2
Density (g/m^3)	7.31- 7.50
Tensile Strength (GPa)	0.95
Modulus of Elasticity (GPa)	11.00

The research's aggregates were analysed using sieve analysis to ensure they met the Superpave standard's gradation requirements. The test procedure involves drying the aggregate sample in an oven at 100°C for 24 hours before sieving. Handling the sample gently during this process is essential to prevent aggregate segregation. The sieve analysis series follows the Superpave standard gradation. This test will help to ensure that the aggregate volumetric in the mixture is suitable for use in asphalt pavements and will meet the requirements for strength and durability [27].

After the aggregate sample has been dried and carefully handled, it is poured onto a series of sieves of varying sizes and set in a vibrator. Typically, the sieving process takes about 10 minutes. According to the sieve size, the aggregate is then separated and stored. The aggregate grading is determined by plotting the percentage of aggregate passing through each sieve on a semi-log graph. This graph assesses aggregate gradation and ensures that it falls within the Superpave standard's parameters. The chart will display the aggregate percentage within each size range and whether or not it is properly graded. This information is crucial for determining whether the aggregate is suitable for bituminous concrete mixtures.

(a) coarse aggregate, fine aggregate, and mineral filler (b) Sieved aggregate according to 12.5 NMAS

Fig. 1. Coarse aggregate, fine aggregate, and mineral filler content (b) Sieved aggregate according to 12.5 NMAS

This study will use an asphalt binder of 60/70 grade for HMA. Table 2 shows the asphalt binder properties.

Table 2
The standard of physical properties for 60/70 asphalt grade

Characteristic	Test Method	Requirement
Penetration at 25^{o}C, 100g	ASTM D5	60-70
Softening Point (^{o}C)	ASTM D36	45-53
Ductility at 25^{o}C, 5cm per min,	ASTM D113	Min. 100
Viscosity at 135^{o}C, 165^{o}C (cp)	ASTM D4402	Max. 1.00
Loss on heating, (%)	AASTHO T240	Max. 1.00
Unaged G*/sin δ at 64^{o}C @ 10	AASTHO TP5	Min. 100
Specific Gravity at 25^{o}C	ASTM D70	1.01-1.05

A dynamic creep test will be used to determine the efficiency of WSF on hot-mix asphalt mixtures at UTHM's Transportation and Highway Laboratory. The Superpave Mix Design process comprises several steps, the first of which is material preparation, and the test is divided into stages. This study will utilise the Superpave gyratory compactor (SGC) to prepare HMA samples to evaluate mechanical and volumetric properties, as per AASHTO T312.

Each sample requires 1,200 grams of asphalt mixture for the study. The asphalt binder is then applied until the desired density is achieved. Before adding the steel fibres (WSF), the mixture was manually blended with mechanical blending according to the percentage of asphalt binder (0, 1, 3, and 5 per cent). The volumetric properties of the asphalt mixture were determined based on ASTM D2726, Maximum Theoretical Specific Gravity G_{mm}, and Bulk Specific Gravity G_{mb} methods.

2.2 Determination of Optimum Bitumen Content (OBC)

This study will prepare sixteen samples using 4%, 5%, 5.5% and 6% bitumen with 0, 1%, 2% and 3% WSF added by total mix volume for a specific grade. The samples were tested for mechanical and volumetric properties according to the ASTM-D 1559 standard. An aggregate batch weighing about 1200g was used for each sample. OBC was calculated using a 4% air void.

2.3 Mechanical Performance Test

The performance testing of the asphalt mixture was conducted to evaluate the strength performance of the rutting behaviour of the waste steel fibre asphalt mixture (WSFAM). This investigation will employ the Dynamic Creep Test for testing. In the study, each aggregate size will be sieved separately before being batched. The base binder 60/70 penetration grade will be heated for two hours at the same mixing temperature of 165°C before mixing. The OBC data is used to prepare twelve samples. The modified mixture will differ from the virgin mixture in that steel fibres will be added in percentages of 0, 1, 3, and 5% by the total weight of the mix. The asphalt mixture will be mixed at a temperature of 155 °C for about two minutes until the aggregate and steel fibres are fully coated with asphalt cement. To achieve a 4% air void, the mixes will be compacted using a Superpave gyratory compactor machine at 100 gyrations. The mixtures will then cool overnight at room temperature before testing.

Dynamic Creep Test is a vital test to determine accumulated strain (MicroStrain), Dynamic Creep Modulus (DCM), Creep Steady Slope (CSS) and Permanent Deformation. A dynamic creep test will be performed to evaluate the asphalt mixture's persistent deformation. The test samples are cylindrical with a diameter of 100 mm and a height of 65 mm. They are compacted with the optimal bitumen content. The Universal Testing Machine (UTM-5P) was used to conduct the test. The test simulates the load of low-volume and high-volume vehicles with loads of 200kPa [28]. The asphalt mixture test specimens will be conditioned for 120 seconds under a 10 kPa conditioning stress. The test will be terminated after each sample has undergone 3600 cycles, and the results for permanent deformation and creep modulus will be recorded. The specimens will be conditioned for 2 hours in an oven to reach a uniform temperature before testing. The parameters used for this performance test are summarised in Table 3.

Table 3
Dynamic Creep Test Parameter

Parameter	Information
Temperature (ºC)	40
Pulse width (ms)	100
Rest period (ms)	900
Contact stress (kPa)	9
Deviator stress (kPa)	200
Stop test after cycle	3600
Temperature (ºC)	40

After conducting the dynamic creep test, several rutting parameters were measured to evaluate the performance of the asphalt mixture. The parameters of interest included the Dynamic Creep Modulus (DCM), Coefficient of Stiffness (CSS), and permanent deformation. These parameters were calculated using the cumulative strain data obtained at cycle 2000 and cycle 3600. The Dynamic Creep Modulus provides crucial insights into the asphalt mixture's stiffness and resistance to deformation under dynamic loading conditions. It offers valuable information on the ability of the mix to withstand repeated loading and resist permanent deformation or rutting [29].

By analysing the cumulative strain data and calculating the DCM, it is possible to evaluate the efficacy of the asphalt mixture. This data facilitates making informed decisions regarding mixture design, pavement design, and maintenance strategies to ensure long-term durability and rutting resistance. Utilising the following equation, the Dynamic Creep Modulus (DCM) was determined using the following calculation method:

Where;

$$\text{DCM} = \frac{applied\ load\ stress}{\epsilon 3600 - \epsilon 2000} \tag{1}$$

$\varepsilon 3600$ = Accumulated strain at 3600 cycle
$\varepsilon 2000$ = Accumulated strain at 2000 cycle

CSS is utilised to evaluate the ability of a sample to return to its original shape while resisting persistent deformation. A lower slope indicates greater elasticity and the sample's ability to recover its original form after being loaded [30]. A more downward slope indicates greater elasticity and the sample's ability to recover its original shape after loading. A higher slope indicates more significant deformation and a reduced ability to regain its original form. The slope of the creep strain can tell whether a material is resilient and resistant to permanent deformation. The CSS formula is displayed in the accompanying equation.

$$\text{CSS} = \frac{\log c3600 - \log c2000}{log3600 - log2000} \tag{2}$$

3. Results

3.1 Gradation of Aggregate

Superpave aggregate gradation consists of three components: coarse aggregate, fine aggregate, and mineral filler. Coarse aggregate is typically 19 to 37.5 mm (0.75 to 1.5 inches) in size, while fine aggregate generally is less than 4.75 µm. Mineral filler, which fills voids, passes a 75 µm test.

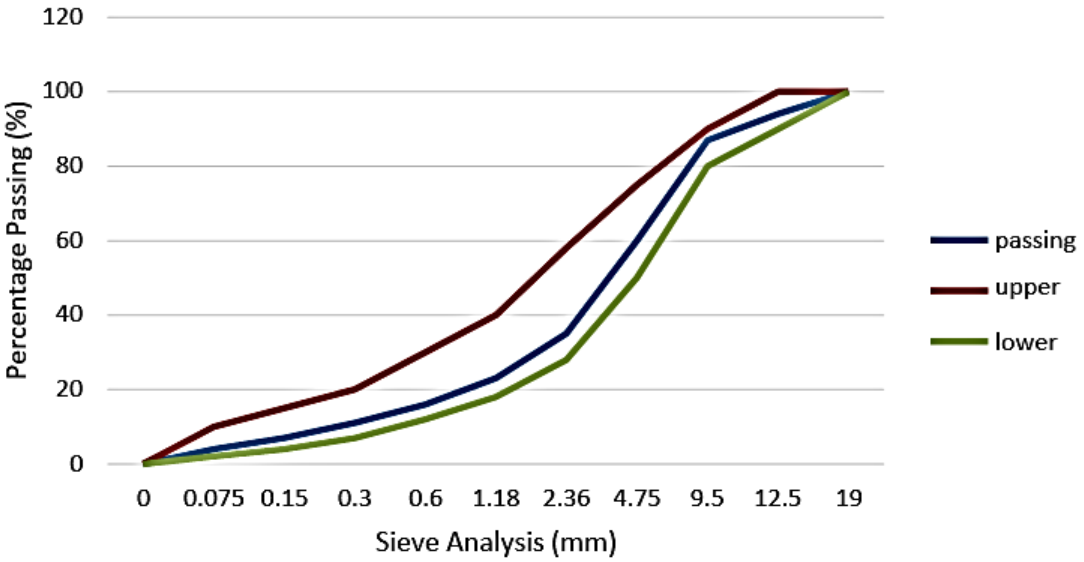


Fig. 2. Percentage passing (%) against Passing line, upper line and lower line(mm)

3.2 Optimum Bitumen Content

The OBC of the specimen was established using 12.5 NMAS. Four trial bitumen contents of 4.5%, 5%, 5.5%, and 6% were conducted using virgin bitumen to determine the optimum bitumen. Laboratory testing was performed on asphalt mix samples prepared with each of these bitumen contents. The samples were compacted using Superpave compaction methods, AASHTO T312, following standardized procedures. Properties of the trial blend were determined and tabulated, as well as the parameters of the asphalt mixture, which are air voids (VA), voids in mineral aggregates (VMA) and air voids filled with asphalt (VFA). Based on the obtained air void content and other considerations within the Superpave mix design methodology, the optimum bitumen content for the asphalt mixture is determined to be 5.5%. The selection of this specific bitumen content is aimed at achieving the desired balance of performance characteristics, such as durability, stability, and resistance to moisture damage.

Table 4

Volumetric Properties of Asphalt Mixture at N_{design}

Trial	Binder content	Va (%)	VMA (%)	VFA (%)
1	4.5	5.439331	14.8	60.4
2	5	4.471545	15.6	68.69
3	5.5	3.797468	16.2	73.55
4	6	2.953586	14.6	79.13
OBC at	5.5	4	-	-
Superpave Criteria	5.5	4	min 14%	65-75

3.3 Dynamic Creep Test

The dynamic creep test is a standard method for evaluating the resistance of asphalt mixtures to permanent deformation or rutting. This test is conducted by subjecting a cylindrical specimen of the asphalt mixture to a constant load or tension while cycling temperature and deformation multiple times. The test assists in determining the bitumen mixture's susceptibility to deformation under traffic loads and high temperatures.

In this investigation, the performance of 12 samples was evaluated using the dynamic creep test. The samples included both control and samples with variable amounts of waste steel fibre as an additive. At 2000 and 3600 cycles, the accumulated strain values for each percentage of waste steel fibre were recorded. As the rate of waste steel fibre increased, the accumulated strain decreased, indicating an increase in resistance to permanent deformation. Table 5 summarises the accumulated strain values for each percentage of waste steel fibre, highlighting the decreasing trend with increasing fibre content, also visualised in Figure 3.

Table 5

Results of accumulated strain values for each percentage of waste steel fibre

Waste Steel Fibre (%)	Applied load(kPa)	Accumulated strain (με)		Accumulated strain (ε)	
		2000 cycles	3600 cycles	2000 cycles	3600 cycles
0	200	3839.134	4128.211	0.0038	0.004128
1	200	13799.73	14626.53	0.0138	0.014627
2	200	32599.36	34908.24	0.0325	0.034908
3	200	42332.66	48425.76	0.0423	0.048425

Using a line graph in Figure 3, the accumulated strain for each percentage of residual steel fibre was compared to the number of cycles. The diagram clearly illustrates the differences in the accumulated strain between the control sample and the modified samples with varying percentages of waste steel fibre. As the rate of waste steel fibre increased, the accumulated strain also increased, indicating a higher susceptibility to permanent deformation.

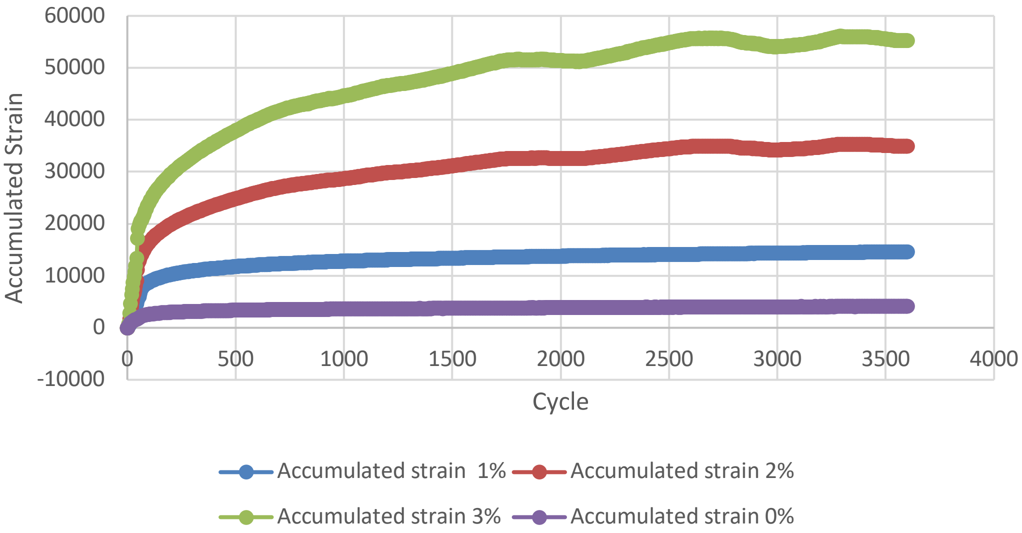


Fig. 3. Accumulated strain (Micro strain) against cycles and comparison in percentage of Waste Steel Fibre

According to the data of accumulated strain (microstrain) recorded in Table 6, the control sample had the lowest value of accumulated strain after the maximal cycle. The modified samples exhibited an increasing trend in accumulated strain with the addition of residual steel fibre. The rutting performance of waste steel fibre as an additive in asphalt mixture was evaluated using three parameters: Dynamic Creep Modulus (DCM), Creep Strain Slope (CSS), and Permanent Deformation. The results of these parameters are summarised in Table 6.

Table 6
Results of DCM, CSS, and Permanent Deformation for each percentage of Waste Steel Fibre

Waste Steel Fibre (%)	Dynamic Creep Modulus, DCM(MPa)	JKR/SPJ/200 8-S4 Requirement	Creep Steady Slope, CSS	JKR/SPJ/2008-S4 Requirement	Permanent Deformation (mm)
0	691.8571868	>75MPa	0.123510	< 0.25	0.2948
1	241.8958832		0.098995		1.037
2	86.62227275		0.116420		2.4866
3	32.82401405		0.228779		3.8615

3.4 Dynamic Creep Modulus (DCM)

DCM is a crucial parameter that reflects an asphalt mixture's resistance to deformation under dynamic loading conditions. The DCM values demonstrate the relationship between WSF content and the dynamic stiffness of asphalt mixtures in the context of the provided data. As the WSF content increases from 0% to 3%, the DCM values decrease, as shown by the analysis of the DCM values. This indicates that higher WSF content is associated with a reduction in the dynamic stiffness of the asphalt mixtures. In simpler terms, the asphalt mixtures with higher WSF content exhibit lower resistance to deformation under dynamic loading.

The decrease in DCM values with increasing WSF content suggests that adding waste steel fibres affects the interlocking and binding characteristics within the asphalt mixture. Fibres may create discontinuities or disruptions in the asphalt matrix, decreasing the overall dynamic stiffness and a higher susceptibility to deformation under dynamic loading conditions.

Therefore, based on the provided data, it can be inferred that increasing the WSF content in the asphalt mixtures results in decreased dynamic stiffness or resistance to deformation. This highlights the importance of carefully considering the appropriate WSF content to balance rutting resistance and dynamic stiffness in asphalt pavement design and construction. The graph in Figure 4 illustrates how DCM values decrease as the percentage of waste steel fibre increases, highlighting the trend of reducing rutting resistance with increasing fibre content.

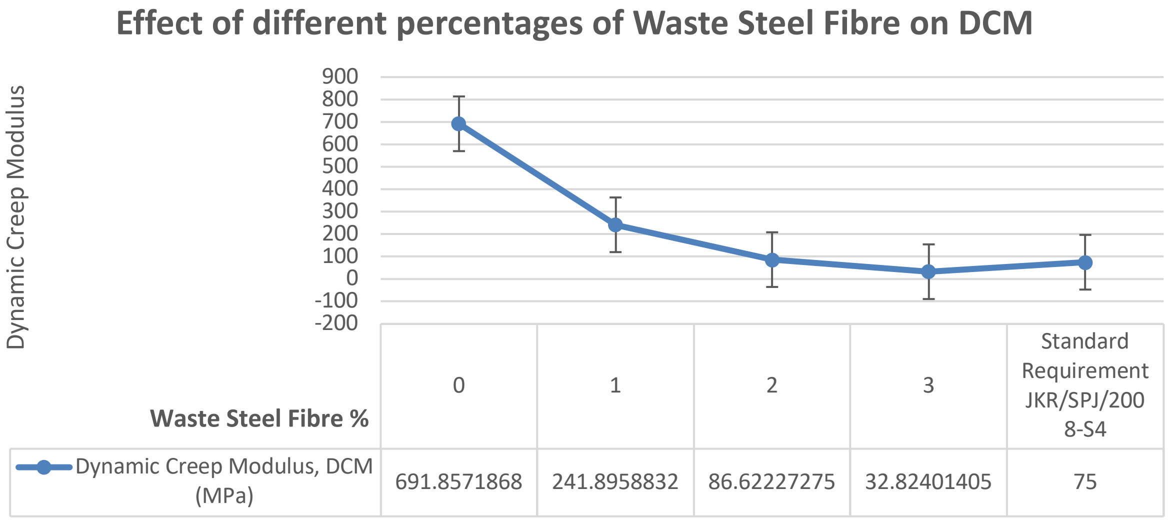
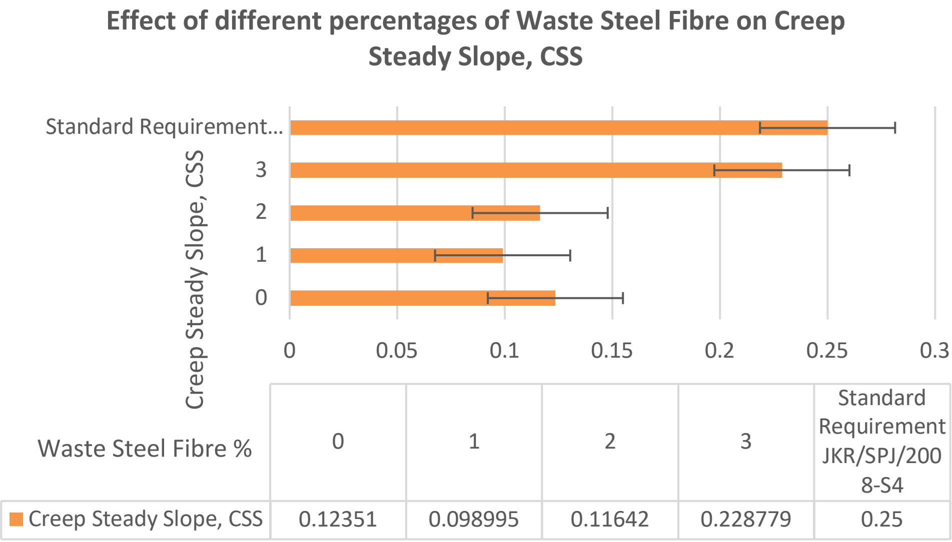


Fig. 4. Effect of different percentages of Waste Steel Fibre on DCM

3.5 Creep Steady Slope (CSS)

Based on the CSS data value, it is proven that the sample with 1% WSF content demonstrates the lowest CSS value of 0.098995, indicating the highest resistance to rutting among the tested samples. This implies that the asphalt mixture with 1% WSF content is less susceptible to permanent deformation under load, making it more resilient against rutting. On the other hand, the samples with 0% and 2% WSF content exhibit CSS values of 0.123510 and 0.116420, respectively. These values suggest a moderate resistance to rutting for both samples, indicating a relatively balanced performance in terms of permanent deformation resistance. Somehow, the sample with the highest WSF content of 3% shows the highest CSS value of 0.228779. This implies that the asphalt mixture with 3% WSF content is more prone to permanent deformation under load, indicating a lower rutting resistance than the other samples. In summary, the data analysis highlights the impact of WSF content on the rutting resistance of the asphalt mixtures. The sample with 1% WSF content exhibits the highest resistance to rutting, while higher WSF percentages (2% and 3%) result in decreased resistance to permanent deformation.



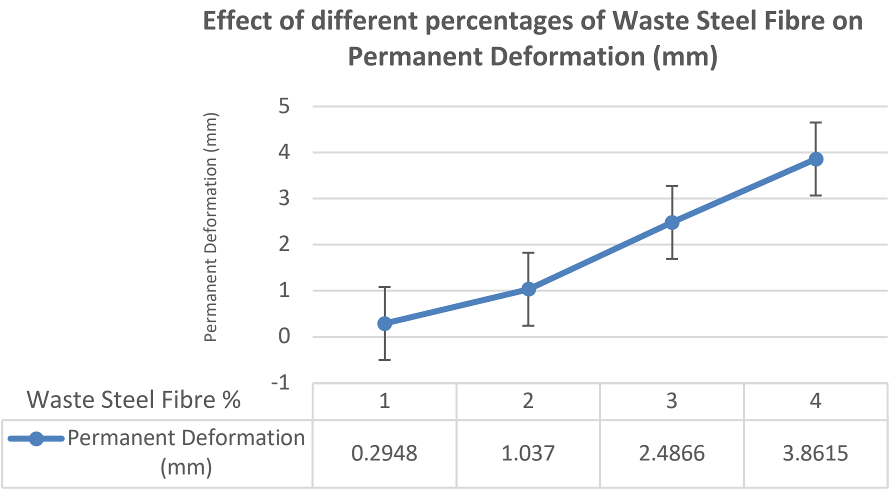
Waste Steel Fibre %	0	1	2	3	Standard Requirement JKR/SPJ/2008-S4
🟧 Creep Steady Slope, CSS	0.12351	0.098995	0.11642	0.228779	0.25

Fig. 5. Effect of different percentages of Waste Steel Fibre on CSS

3.6 Permanent Deformation

The permanent deformation values indicate the extent of deformation or rutting in the asphalt mixtures under applied loads [16]. Higher values of permanent deformation values susceptibility to rutting and reduced resistance to long-term deformation [31]. From the provided data, it can be observed that as the WSF content increases, the permanent deformation also tends to increase. The asphalt mixture with 0% WSF content exhibits the lowest permanent deformation value of 0.2948 mm, indicating relatively better resistance to rutting. On the other hand, the samples with WSF contents of 1%, 2%, and 3% show higher permanent deformation values of 1.037 mm, 2.4866 mm, and 3.8615 mm, respectively. These larger deformation values suggest that asphalt mixtures with higher WSF content are more prone to rutting and exhibit reduced resistance to long-term deformation.

The data shows a clear correlation between WSF content and permanent deformation in the asphalt mixtures. Higher WSF content tends to increase deformation, indicating a higher susceptibility to rutting. Therefore, carefully considering the tent is crucial to mitigate rutting and ensure adequate long-term performance of the asphalt pavement, which reduces resistance to long-term deformation.



Waste Steel Fibre %	1	2	3	4
Permanent Deformation (mm)	0.2948	1.037	2.4866	3.8615

Fig. 6. Effect of different percentages of waste steel fibre on permanent deformation(mm)

4. Conclusions

This research aimed to assess the strength performance and rutting behaviour of a waste steel fibre asphalt mixture. The lower percentage of waste steel fibre exhibited lower DCM values, indicating less resistance to deformation under repeated loads. This suggests that the addition of waste steel fibre, which is more than 1%, is unable to enhance the rutting resistance of the asphalt mixture. This result is the same as Guo and J's conclusion that the stability is unrelated to the fibres. The strengthening effect will only be achieved if the percentage of steel fibres corresponds to the amount of asphalt supplied [7,14].

CSS values demonstrate that the asphalt mixture with 1% WSF content exhibits the lowest CSS value, indicating higher resistance to rutting compared to the other samples. Previous studies also stated that the mixture's susceptibility to pavement rutting corresponds to CSS, with the lowest CSS found in the mixture containing 1% steel fibre. This demonstrated that the mix with the lowest CSS could resist more rutting [18].

Permanent Deformation data obtained for permanent deformation revealed that the control sample (0% waste steel fibre) had the lowest values, indicating better resistance to permanent deformation. However, as the percentage of waste steel fibre increased, the permanent deformation also increased. This suggests that adding waste steel fibre may harm the asphalt mixture's rutting resistance and long-term performance. Based on a previous study, using a range of less than 1 per cent is recommended. The study found an increase in performance of 0.3 per cent, indicating the optimal value for using steel fibre in SMA [32].

The optimal fibre content in the asphalt mixture might exist, beyond which further increases may not yield significant benefits or could even have adverse effects on other properties of the mix. The selection of the percentage of steel fibre between 1% and 3% yields an unsatisfactory value; consequently, it is recommended that the rate of use of steel fibre begins at 1% and is far less than 1% to obtain the optimal value for the benefit of added steel fibre in asphalt pavement. This result is in line with what was observed by Serin *et al.,* [33] where the optimum value for fibre rate resulting in the best stability value determined at 0.75%. The study's results indicated that steel fibre additions can enhance the stability of the binder course in the flexible pavement with these values. The same goes for Köfteci [34] an investigation was conducted on five asphalt samples containing different percentages (1%, 3%, 5%, 7%, 9%) of Low-Cost Iron Wire Fiber to study their stability and moisture impact using Indirect Tensile Strength (ITS) and Tensile Strength Ratio (TSR) tests. The findings from Köfteci revealed that incorporating low-cost iron fibre led to a 1% to 3% increase in the quality of asphalt mixtures. Clustering of fibres was observed under a stereomicroscope when the fibre content exceeded 3%. This led to decreased interaction between bitumen and aggregates, resulting in increased air vacuums. However, higher fibre percentages (7–9%) caused the mixture's compression, durability, and stability issues.

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