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Statistical Approach Model to Evaluate Permanent Deformation of Steel Fiber Modified Asphalt Mixtures

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Abstract: A good asphalt mixture is very important to maintain the triangle of sustainability. Many accidents occur due to pavement damage such as permanent deformation caused by the external loads induced by heavy traffic. Stone Mastic Asphalt (SMA) has a low resistance to moisture and other performances. Many researchers have conducted on SMA using various types of fiber. However, not much research has been done using steel fiber in the SMA mixture and has analyzed the result obtained using a statistical approach. The objective of this research was to identify the optimum amount of steel fiber in a modified asphalt mixture and characterize the performance of steel fiber in the SMA mixture using the statistical approach of Response Surface Methodology (RSM) in Design Expert Software. In this study, various steel fiber proportions of 0 percent, 0.3 percent, 0.5 percent, and 0.7 percent by the total weight of the SMA mixture were used. The Marshall stability and flow test, dynamic creep and moisture susceptibility test, and ultimately, RSM analysis were used to evaluate the properties and performance of the steel fiber-modified SMA, which contained 6.2 percent of PEN 60/70 asphalt binder content. The testing findings unmistakably demonstrated that the addition of steel fiber greatly improves the SMA mixture's resistance to moisture and permanent deformation. An amount of 0.3 percent was found to be the most optimum steel fiber content from the optimization by using Response Surface Methodology, thus proven with additional steel fiber in the SMA mixture enhancing the performance of the mixture. As a result, it can be determined that the addition of steel fiber to SMA asphalt mixtures has improved the properties and performance in the construction of asphalt pavements, and the RSM method is an efficient statistical method for producing an appropriate empirical model for relating parameters and predicting the best performance of an asphaltic mixture.

Keywords: steel fiber; dynamic creep; moisture susceptibility; stone mastic asphalt; response surface method

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1. Introduction

Approximately, 60,000 km covering each state shows that Malaysia has one of the finest network systems, and the major types are flexible pavement and a small part of pavement made from concrete (rigid pavement). Flexible pavement is a mixture of asphalt binder and aggregates which are heated and mixed, and then laid and compacted above a granular layer; meanwhile, rigid pavement is a mixture of cement concrete and is laid over a dry lean concrete. The rigid concrete can also be compacted above the layer of aggregates. In the past, a thousand years ago, roads were being used in our daily lives. Both types of pavements will not last forever, in which they must be monitored regularly. Thus, improvising and making these roads better and safer for all users is a must to lessen road destructions and indirectly reduce road fatalities.

Every year, governments invest a lot of money to maintain and repair road conditions, and this indirectly affects the economy of the country. The road conditions in Malaysia, which were constructed using the conventional method, have a short lifespan and needed to be maintained regularly due to road defects (potholes) leading to 11.2 percent of road accidents [1]. Furthermore, the changes in weather and temperature affect the roads; for instance, Malaysia, with its tropical monsoon climate, makes the pavement repetitively experience hot and wet conditions. The increasing number of road users leads to an increase in load stress and traffic volume, thus making the road surface experience more impacted in terms of stripping, potholes, and permanent deformation of repetition load.

Next, Stone Mastic Asphalt (SMA) is designed specifically to reduce rutting and skid resistance, as all aggregates have a stone-to-stone contact. Stone Matrix Asphalt (SMA) is a gap-graded bituminous mixture that has a comparatively higher proportion of coarse aggregates and binder mastic with a bituminous binder and mineral filler. A major problem with SMA is the drain down of mastic content at different phases of construction. This situation occurs due to SMA's high coarse aggregate content, which creates gaps in the structural matrix and causes those voids to be filled with high-viscosity bituminous mastic with any stabilizing material, such as bitumen, crushed sand, or filler. Usually, additional fiber additives or a stabilizing agent material are used to stabilize the mixture and prevent binder drainage in stone mastic asphalt mixing [2,3]. Fiber reinforced bituminous mixtures are commonly used in the industry. However, research on the attributes and performance of stone mastic asphalt (SMA) using steel fiber is rather under published and has not yet been conclusively shown.

Various types of additives and modifiers were used in SMA to modify asphalt pavement. Ali et al. [4] used mineral fiber, cellulose fiber, and styrene–butadiene–styrene (SBS) to modify stone matrix asphalt (SMA) mixtures, and performance tests were performed for modified and unmodified mixtures. According to the findings, SBS was superior to fibers in terms of improving the performance of asphalt mixtures and the service life of the pavement system modified with mineral, cellulose, and SBS was 1.07, 1.081, and 1.243 times longer than that of the unmodified mix, respectively. Another piece of research by Goutham Sarang et al. [5] prepared mixtures with four different shredded waste plastics' (SWP) content, and another mixture without any stabilizers was also prepared using polymer modified bitumen (PMB). Tensile strength, moisture susceptibility, rutting resistance, and fatigue behavior were determined using the obtained optimum bitumen content (OBC). The research findings indicated that the optimum level of SWP in the SMA mixture was selected as eight percent by the weight of bitumen. The result revealed that although a mixture with PMB performed the best, SMA with eight percent of SWP produced equivalent results. Therefore, it can be concluded that waste plastic in SMA should be used instead of a stabilizing additive.

As the number of registered vehicles in Malaysia increases, the quality of pavement needs to be improved as well, in order to resist the amount of stress and strain on the road. The presence of a good modifier has proven to reduce the asphalt binder content, increase the stability in the road mixture, and also strengthen the bond between aggregates and the fillers [6]. For the purpose of improving the performance of road pavement, a modified asphalt mixture is essential. Many researchers have worked with various modifiers and additives such as polypropylene, polyethylenes, acrylonitrile butadiene styrene, styrene-butadiene-styrene, polyvinyl chloride, and polyethylene terephthalate [7]. Recently, the use of fibers in asphalt mixtures is one of the many alternative materials that has been demonstrated to increase the stability and resistance against moisture damage of asphalt mixtures in dealing with pavement distresses. Previous studies have found that using fiber has become a significantly attractive option in road construction. In addition, many studies have reported that the use of fibers is beneficial for enhancing the strength of hot mix asphalt mixtures. Fibers can be used, particularly in SMA mixtures, to prevent asphalt from deteriorating during transportation and mixture construction [8–10]. The addition of fibers changes the mixture's viscoelastic properties, improves its dynamic modulus, increases its sensitivity to humidity, offers resistance to rutting, and reduces the number of reflective cracks in asphalt pavement [11–16]. This finding is consistent with research by previous researchers which indicates the addition of fibers modifies the mixture's viscoelasticity, increases its dynamic modulus, increases sensitivity to moisture, enhances flow coherence, and provides rutting resistance [17–22].

Synthetic fibers, glass fibers, natural fibers, and steel fibers are among the polymer fibers that are frequently added to asphalt mixtures. Steel fibers are classified as metallic fibers or mineral fibers. It is a mineral fiber that was used as a fiber-reinforced material to enhance the tensile strength. The use of this fiber encourages the transformation of asphalt qualities into high-performance asphalt. Currently, the use of steel fiber in cement and concrete pavements has recently been the subject of some investigation [23–26]. The effect of micro steel fiber percentage (0.1 percent, 0.2 percent, 0.3 percent, and 0.4 percent) by volume of the total mix on the different grades, volumetric properties, and mechanical properties were determined by the Marshall method at different temperatures (50, 60, 70) °C and different compaction blows (50, 75, 125). The research findings indicated that the stability of hot mix asphalt increased when steel fiber was added, and then decreased in a crest-like manner. This indicates that using steel fiber as a modifier additive has improved Marshall Stability compared to using a conventional mixture without fiber [26].

Research conducted by Serin et al. [18] specimens were produced using different fiber rates (0 percent, 0.25 percent, 0.50 percent, 0.75 percent, 1.0 percent, 1.5 percent, 2.0 percent, 2.5 percent) and tested under the Marshall Stability Test, and the optimum bitumen content value for the aggregates sample to be used was determined. Results showed that the optimal value for the fiber rate that results in the best stability value was determined to be 0.75 percent. Steel fiber additions can therefore be used in the binder coarse of the flexible pavement due to their positive stability impact. Another piece of research by Ahmed and Mahmood [27] used different types of mineral fibers. This research examined the potential of using different mineral fibers to withstand pressures on the pavement's surface layer. Steel, aluminum, copper, and tin were the four different types of mineral fibers used in this research, along with four different fiber rates (1 percent, 1.5 percent, 2 percent, 2.5 percent) by total weight of the mixture, varying mineral fiber lengths (0.5, 1.0, 1.5, and 2.0 cm), and four different thicknesses (0.2, 0.4, 0.7, and 0.9 mm). According to the findings, adding copper fiber with a total weight of 1.5 percent, and dimensions of 0.5 cm in length and 0.4 mm in thickness, increased the Marshall stability by 34 percent, as compared to a conventional mix.

The use of statistical modelling and optimization approaches is effective in handling a variety of constraints, objectives, and articulating the interactions between dependent variables that influence a certain response [28]. In order to meet the demand for the optimization approach, Response Surface Methodology (RSM), a statistical technique using Design Expert Software, was used to identify the most optimal properties from the experimental data. RSM is the most popular design of experiment (DOE) for optimization, which improves a system's operational parameters and conditions [29]. Regrettably, there are not many expert practices in this sort of procedure since the researcher must have excellent statistical and numerical skills. RSM is increasingly being used in asphalt research since it not only saves time and money, but also can predict if a material will persist over time, which is beneficial economically in the long term. Regression modelling, the central composite design (CCD) approach, and analysis of variance (ANOVA), which take a number of various factors and responses into consideration, have all been employed. [30]. RSM techniques have been successfully used in a variety of fields, including biomass and clay science, material and mechanical engineering, and concrete technology.

The addition of steel fiber made in the modification of an asphalt mixture can enhance the asphalt mixture properties and mechanical performances and reduce the distress problems of a pavement which provides a safer road. The properties of steel fiber that are strong can increase the properties of the road mixture which provide a positive stability impact. Steel fiber is one of the fibers that has good properties as a modifier. Additionally, steel fiber-modified asphalt mixtures can reduce the cracking of the pavement, and increase its performance in the resistance to damage not only caused by concentrated loads, but also impact loading [18,31].

Therefore, in order to test the effect of mixture properties on asphalt performance associated with sensitivity to moisture and dynamic creep, steel fiber in various proportions (0 per cent, 0.3 percent, 0.5 percent, and 0.7 percent) was studied as a modifier in this study. The proportion of steel fiber was selected according to research conducted by AL-Ridha et al. [26]. From Serin et al. [18] and Ahmed and Mahmood [27], the average optimum proportion of steel fiber that significantly improved the properties and performance of the asphalt mixture is between 0.5 percent to 0.75 percent. RSM was used to optimize and develop models for predicting the optimum amount of the steel fiber in a modified asphalt mixture and characterize the performance of steel fiber in the SMA mixture. It is thought that the addition of steel fiber to the asphalt mixture might offer excellent potential for pavement performance. Additionally, it is supposed that the enhanced characteristics of the asphalt pavement using steel fiber in the SMA asphalt mixture are significant. In that case, it can increase the durability of the asphalt pavement while reducing the need for maintenance, thereby extending the pavement service life and eventually reducing maintenance costs in the long run.

2. Materials and Methodology

The objective of this research was to identify the optimum amount of steel fiber in a modified asphalt mixture and characterize the performance of steel fiber in the SMA mixture using the statistical approach of Response Surface Methodology (RSM). The hypothesis of this research is: do different proportions of asphalt and modifier content affect the performance of the modified SMA mixture? and how does the particular modelling approach evaluate and optimize the content of steel fiber in the SMA modified asphalt mixture to the performance of the asphalt mixture? In response to the need for the optimization of the asphalt and modifier content, a statistical approach of Response Surface Methodology (RSM) was used to find the most optimum properties from the experimental data by using Design Expert Software. The experimental process was divided into a few stages where each stage focused on achieving different objectives. The initial stage was focused on determining the optimum amount of steel fiber in a modified asphalt mixture by using Response Surface Methodology. The following step was to create models using CCD which is based on ANOVA, and the final stage was to observe the similarity of the output by using Response Surface Methodology with the laboratory data on mechanical performances of different percentages of steel fiber in the modified asphalt mixture. All tests which were conducted to achieve the objectives of the research are discussed in this chapter. The experimental process is shown in Figure 1.

2.1. Materials and Sample Preparation

This research was carried out by using local materials that are available in Malaysia. Considering that Kajang Rocks Quarry consistently produces aggregates of high quality and meets the specifications, both coarse and fine aggregates from this quarry were chosen. The selection of a 60/70 penetration grade binder was chosen in consideration of Malaysia's current usage. Steel fiber is added to the SMA mixture to stop the binder drain down from worsening, which enhances the volumetric and mechanical qualities as well as the impact of resistance. The steel fiber, as shown in Figure 2, that was used in this research was sourced by Gardner Global. It is imported from China. The properties of the steel fibers were straight, with dimensions of 0.52 mm in diameter and a length of 35 mm, 7800 kg/m^3

in density, 2600 MPa in tensile strength, and a 65 Aspect Ratio. In this research, the SMA Marshall mix design method has been used in accordance with the JKR/SPJ/S4 [32] to determine the percentage of the optimum asphalt binder. Table 1 shows the aggregate grading used to fabricate asphalt mixture samples.

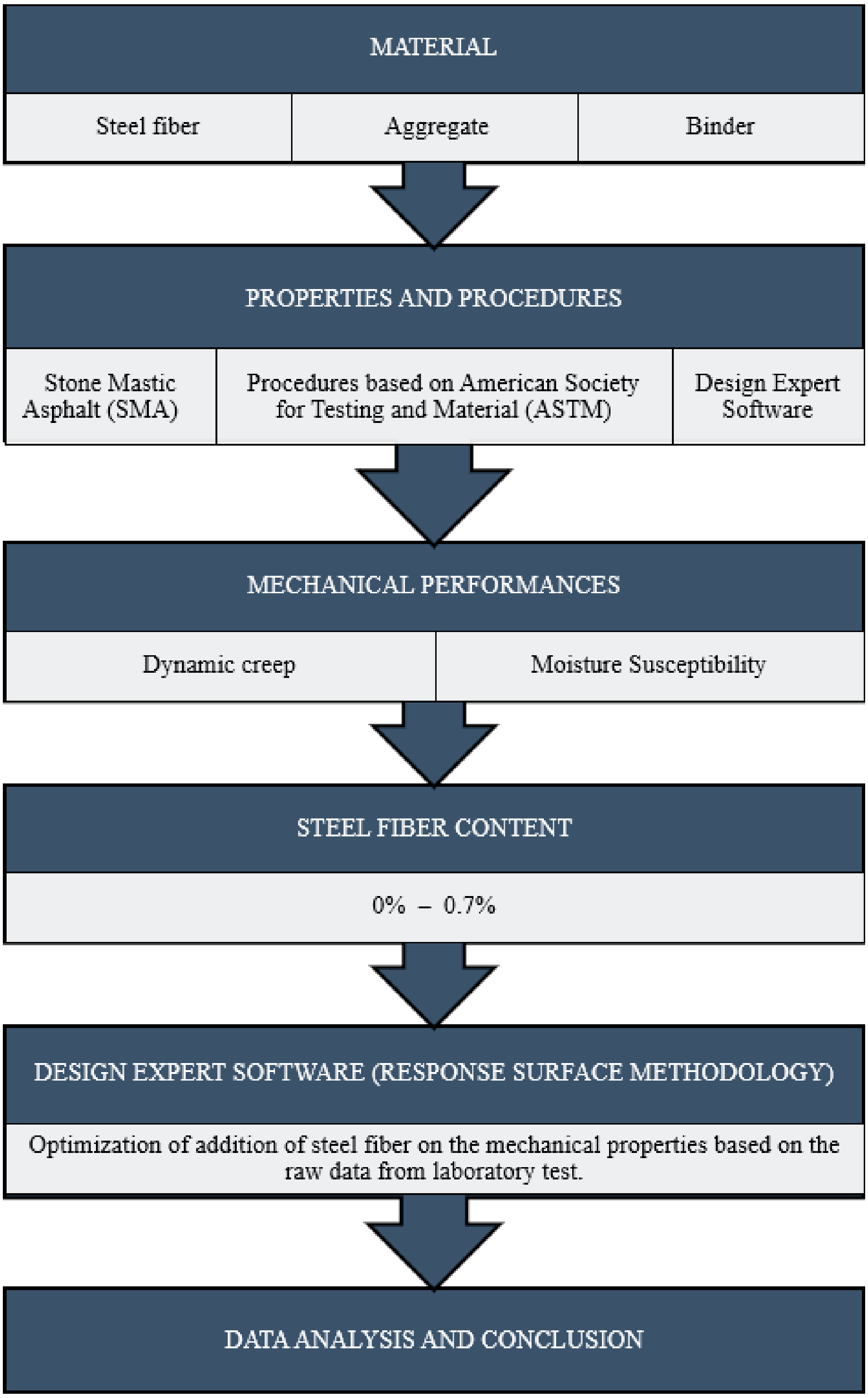

Figure 1. The Flow of Research Process.

Figure 2. Steel fiber.

Table 1. SMA Aggregate Gradation.

Sieve	Gradation		Percentage Passing	Percentage Retained	Mass Passing	Mass Retained
Size	Lower	Upper				
19.0	100	100	100	0.0	1200.0	0
12.5	85	95	90	10.0	1080.0	120
9.5	65	75	70	20.0	840.0	360
4.75	20	28	24	46.0	288.0	912
2.36	16	24	20	4.0	240.0	960
0.60	12	16	14	6.0	168.0	1032
0.30	12	15	13.5	0.5	162.0	1038
0.075	8	10	9	4.5	108.0	1092
Pan				9.0		108

2.2. Marshall Stability & Flow

Marshall samples were prepared in accordance with ASTM D1559. A total of twelve (12) Marshall samples were created by mixing the SMA graded aggregate with 60/70 penetration grade bitumen with the mineral fiber to a desired temperature. As part of the dry blending method procedure, steel fiber was added directly to the mixture at 0, 0.3, 0.5, and 0.7 percent by weight of the mixture before the asphalt binder. All test samples were given 50 blows per face using a standard Marshall compactor. Marshall Stability and flow is essentially a test of a bituminous mixture's resistance to deformation, to preserve it from exposure to the continuous and heavy traffic load. The result of Marshall stability is highly correlated to the tensile strength of the asphalt mixture, whereas Marshall flow is related to the rutting resistance of asphalt mixture, which evaluates the permanent strain that occurs in a Marshall test upon failure. Figure 3 shows the Marshall stability equipment used in this study which evaluates the maximum load resistance that can be applied during the test procedure at 60 °C and a loading rate of 50.8 mm/minute before the compacted samples fail.

2.3. Dynamic Creep Test

The stiffness properties of the mixtures were evaluated using a dynamic creep test. The Universal Testing Machine (UTM 5) (Figure 4) was used to perform the dynamic creep test according to the EN12697-25 standard [33] method which is commonly used to measure the permanent deformation of asphalt mixtures. For two hours, samples were conditioned by being placed in a temperature-controlled cabinet to guarantee that the temperature was attained consistently. The sample was then placed between the platens. The loading axis of the testing apparatus was concentrically lined up with the assembled platens and sample. The displacement measuring device is then attached to the platens, and the linear variable differential transducers (LVDTs) are used to measure the vertical deformation. As indicated in Table 2, the load and other factors in this study were applied in accordance with the test parameter. The accumulated strains were recorded at each load cycle and were terminated after they reached the cycle termination. The accumulated strain was calculated by using Equation (1):

$$\varepsilon = \frac{h}{H_0} \quad (1)$$

where ε is the accumulated strain, h is the axial deformation (mm), and H_0 is the initial sample height (mm). Reporting dynamic creep modulus and slope at a steady state, the latter shall be the log strain divided by log load cycles between 2000 and 3600 loads.

Figure 3. Marshall stability test.

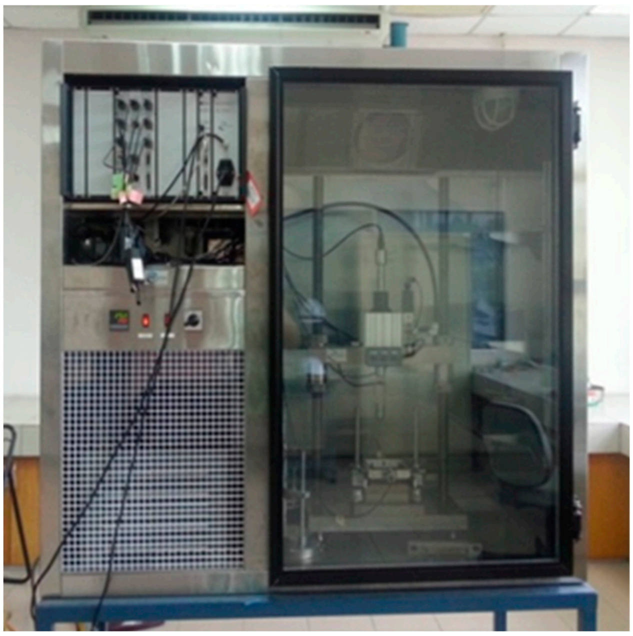

Figure 4. Universal Testing Machine (UTM).

Table 2. Dynamic creep test parameters.

Parameters		Values
Pre-conditioning	Test temperature	40 °C
	Applies axial stress	150 kPa
	Loading frequency	0.5 Hz
	Loading time	0.2 s
	Rest period	1.8 s
	No. of cycles	30
Testing	Test temperature	40 °C
	Applies axial stress	300 kPa
	Loading frequency	0.5 Hz
	Loading time	0.2 s
	Rest period	1.8 s
	No. of cycles	3600

2.4. Moisture Susceptibility Test

The Modified Lottman Test was used to conduct the moisture susceptibility test (AASHTO T283). The moisture susceptibility potential of the asphalt mixture was determined using the Tensile Strength Ratio (TSR), which is the ratio of the average tensile strength of conditioned samples to the average unconditioned tensile strength. The tensile strength ratio (TSR) was used with 80 percent as the boundary between mixtures resistant and sensitive to moisture [34]. Six (6) compacted samples were prepared for each asphalt mixture. Three samples were produced in dry conditions, while three others were produced in wet conditions. The loss of indirect tensile strength (ITS) is used to assess the stripping resistance of asphalt mixtures. An ITS test was performed by compressive loading on the cylindrical samples at a constant rate (50 mm/minute vertical deformation at 25 °C) and measuring the force required (maximum compressive loading) to break the sample. Using Equation (2), the tensile strength of the samples was determined, while Equation (3) was used to determine moisture susceptibility for the asphalt mixture samples. The *TSR* value reveals the mixture's resistance to moisture susceptibility. The distinction between mixtures resistant and susceptible to moisture damage was made using the maintained tensile strength ratio (*TSR*) of 80% [34].

$$ITS = \frac{2000 \times P}{\mu \times h \times D} \quad (2)$$

where, *ITS* is the indirect tensile strength (kPa); *P* is the maximum load (N); *h* is the sample thickness (mm); and *D* is the sample diameter (mm).

$$TSR\ (percent) = \frac{ITS\ cond}{ITS\ Uncond} \quad (3)$$

where, *ITS cond* is the average ITS of the conditioned samples and *ITS Uncond* is the average *ITS* of the dry samples.

2.5. Design of Experiment

Statistical analysis software of Response Surface Methodology (RSM) was used as the main method of the research. From RSM, the problems can be studied in a wider range and multiple numbers of variables. Moreover, it is one of the most used experimental designs for optimization. A Central Composite Design (CCD) was adopted in this research. The design models in central composite design are linear, quadratic, or in higher order. Linear is the lowest order, quadratic is the second order, and meanwhile, higher order is the third order. For this experiment, all three model orders were used as it is suggested by the software for the secondary data obtained. Four types of statistical experiments (one factor, targeted one factor, two factors, and targeted two factors) were done with two methods of analysis: namely, one factor and two factors. The One-factor-at-a-time (OFAT) analysis or linear analysis is used to check how each factor affects the responses. In this OFAT analysis, the interaction only occurs between one selected factor with the response. Next, the two factor analysis is the interaction between various factors with the response. This method is also called quadratic and cubic analysis. From both methods, the optimization was done, and the predicted best value of steel fiber was obtained as well as the value of the responses. Meanwhile, the targeted steel fiber value was done to compare the value of responses in the laboratory experiment and the statistical experiment. All the analyses were carried out using Design Expert Software Version 12. Figure 5 shows the overall flowchart of the data analysis processes in software.

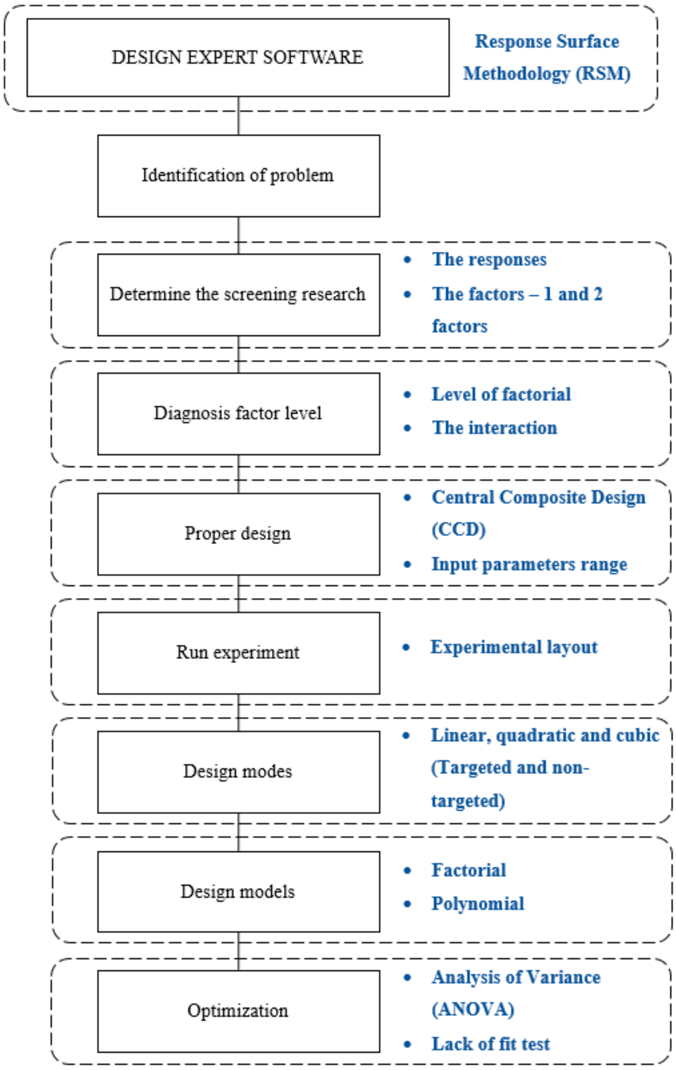

Figure 5. The Overall Flowchart of Data Analysis Processes in Software.

3. Results and Discussion

3.1. Marshall Stability and Flow

Table 3 and Figure 6 illustrate the results of the Marshall stability and flow test of SMA control mixtures and SMA mixtures with various proportions of steel fiber of 0.3 percent, 0.5 percent, and 0.7 percent. Marshall stability values represented in Table 3 specify the maximum load that the mixture samples can sustain before reaching the failure point, whereas flow values indicate the deformation at the maximum load. Both values were obtained directly from experimental work using the Marshall Testing Machine. By referring to Table 4, it indicates that the average Marshall stability of the SMA samples with the incorporation of 0 percent, 0.3 percent, 0.5 percent, and 0.7 percent of steel fiber are 8.7 kN, 10.7 kN, 10.6 kN, and 9.8 kN, respectively. The results present that the stability of SMA mixtures containing steel fiber increases at first, reaches a maximum value, and then begins to decline as the content of steel fiber increases. The inclusion of 0.3 percent of steel fiber in SMA yielded the maximum stability of 10.7 kN. This is due to the small quantity of steel fiber in the mixture, which owing to the contact points between the aggregates, thus leads to a high level of stability.

Table 3. Marshall Stability and Flow result with different percentage of steel fiber.

Steel Fiber (Percent)	Stability (kN)	Flow (mm)
0	8.7	6.25
0.3	10.7	4.87
0.5	10.6	4.70
0.7	9.8	4.42

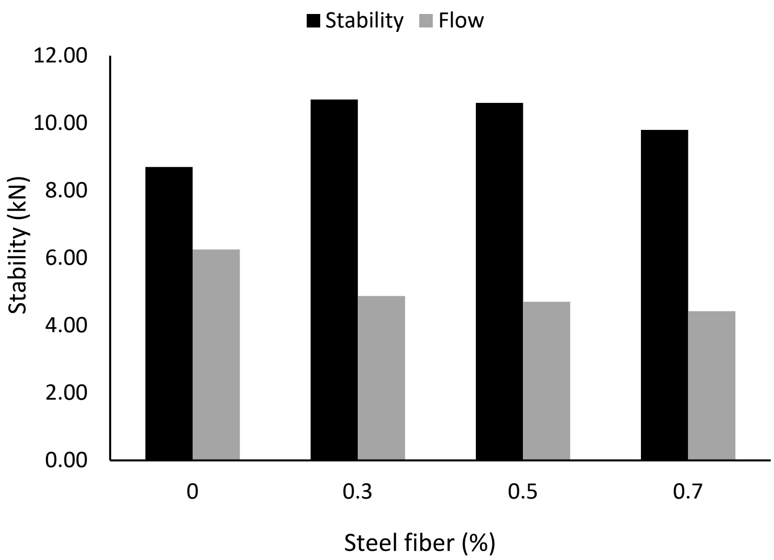

Figure 6. The Stability and Flow values with different steel fiber content.

Table 4. Creep Strain Slope (CSS) (percent).

Steel Fiber Content (Percent)	Creep Strain Slope (CSS) (Percent)	Average Creep Strain Slope (CSS) (Percent)
0	0.092 0.082	0.09
0.3	0.048 0.096	0.07
0.5	0.068 0.163	0.12
0.7	0.161 0.142	0.15

The inclusion of 0.5 and 0.7 percent of steel fiber results in a varied pattern for stability. The stability of the mixture started to decrease with the addition of 0.5 percent and 0.7 percent of steel fiber. A similar finding to previous research presents that the stability increases with 0.2 percent of steel fiber and decreases when fiber content is increased by up to 0.6 percent. This issue occurred because of an excessive amount of steel fiber in the mixture that did not distribute uniformly within the mixture [35]. Comparing the stability value to the control SMA, which had the lowest maximum load, the stability value still increased with the addition of 0.5 and 0.7 percent. Stability improvement can be related to increasing adhesion between the aggregate and asphalt binder. This shows that adding steel fiber to an asphalt mixture, specifically SMA, improves rutting resistance and performance compared to a conventional mixture. This finding is in line with the findings of other prior investigations, which proved that using steel fiber in asphalt mixtures improves stability performance when compared to the conventional mixture [18,22]. In correlation to these obtained results, it is clear that the stability characteristics of the SMA mixes are significantly improved by the addition of steel fiber, which is directly related to an improvement in mixture toughness.

As for the flow values, 6.25 mm, 4.87 mm, 4.70 mm, and 4.42 mm were obtained for steel fiber proportions of 0 percent, 0.3 percent, 0.5 percent, and 0.7 percent, respectively. The flow value indicates the flexibility of the asphalt mixtures. The performance of the modified asphalt mixture shows an inconsistent flow value with the inclusion of steel fiber. Mixtures with 0 percent, 0.3 percent, 0.5 percent, and 0.7 percent of steel fiber obtained flow values of 6.25 mm, 4.87 mm, 4.47 mm, and 4.42 mm, respectively. By analyzing each flow value obtained, it is evident that the flow value of the asphalt mixture tends to reduce slightly with the increasing content of steel fiber. This occurred as a result of the stiffness of the steel fiber in the asphalt mixture, which made the mixture less flexible. In conclusion, it can be indicated that the incorporation of 0.3 percent, 0.5 percent, and 0.7 percent of steel fiber in the asphalt mixture increases the stability up to 23 percent, 21 percent, and 12 percent, respectively, compared to the conventional mixture. In the meantime, the flow values go through a reduction of about 22 percent, 25 percent, and 29 percent with a steel fiber content of 0.3 percent, 0.5 percent, and 0.7 percent, respectively. In relation to these indications, it can be said that the optimum percentage of steel fiber to be utilized in the SMA mixture in terms of stability is 0.3 percent.

3.2. Dynamic Creep

Figure 7 shows the findings of the dynamic creep curve on the SMA mixture with varying steel fiber content. Mixtures with higher cumulative axial strain values have a reduced potential for rutting resistance. This Figure shows that when the load cycle rises, the cumulative permanent strain increases. This implies that these curves significantly diverge from one another. The permanent deformation of the asphalt mixture was clearly affected by steel fiber. It is backed by the outcome, which demonstrated that the mixture's permanent strain increases with increasing steel fiber content. This shows that the resistance to permanent deformation is decreased when steel fiber is included in the SMA mixture.

Comparing the results with conventional as well as other steel fiber proportions, SMA with 0.3 percent of steel fiber demonstrated the greatest improvement in terms of permanent deformation, demonstrating that the addition of steel fiber significantly reduces the strain value when compared to the control mixture. In other words, the SMA mixture containing 0.3 percent of steel fiber is resistant to permanent deformation. The control sample, 0.5 percent of steel fiber combinations, and 0.7 percent of the steel fiber mixture, on the other hand, have a significant value of strain in comparison to the 0.3 percent of steel fiber content. This shows that the control SMA mixture is not resistant to permanent deformation. The result is consistent with research by Jasni et al. [35], where the trend results show the specimens with fiber contents had a decreased strain value. The mixture with 0.5 percent of fiber content exhibited a higher permanent strain value compared to other mixes at 25 °C, while it was 0.4 percent for 40 °C. The asphalt mixture is less prone to permanent deformation if the value for permanent strain from the test is lower. Moghaddam et al. [36] examined the permanent deformation of control and PET-modified asphalt mixtures using a dynamic creep test. The findings concluded that PET significantly enhanced the asphalt mixtures' permanent deformation properties. They also discovered that the mixture with more PET added had improved resistance to permanent deformation.

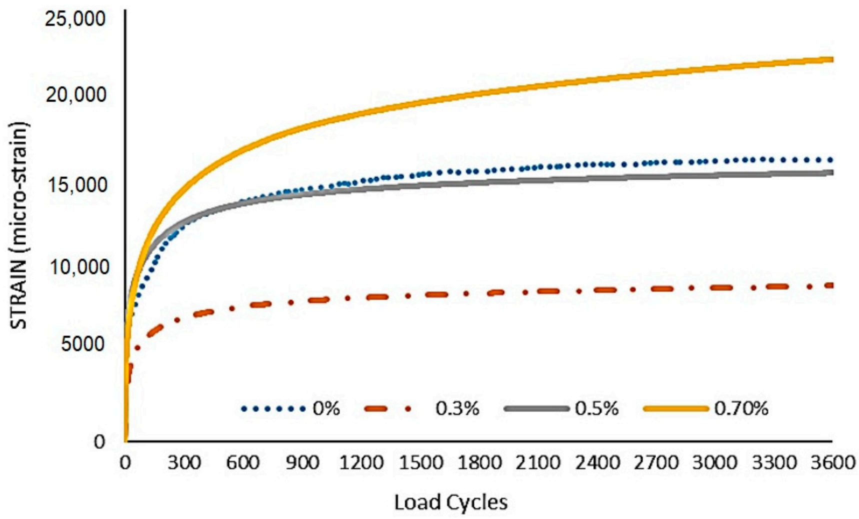

Figure 7. Dynamic Creep Curve of SMA mixture.

A logarithmic strain versus load cycle plot with two linear fits to the dynamic creep curve is used to calculate the Creep Strain Slope (CSS), which is the slope of the secondary stage. During this stage, the creep strain rate is virtually constant under constant stress loading circumstances [37]. As a result, CSS is a term used to characterize the features of permanent deformation that are affected by load cycling. The CSS value was calculated using Equation (4).

$$CSS = \log\varepsilon_{3600} - \log\varepsilon_{1200}/\log 3600 - \log 2000 \quad (4)$$

Table 4 and Figure 8 illustrate the CSS for SMA mixtures with and without steel fiber. Mixtures with 0.3 percent of steel fiber exhibited a significant CSS value, 0.07 percent, which indicated the most resistance to permanent deformation, while mixtures with 0 percent, 0.5 percent, and 0.7 percent of steel fiber obtained CSS values of 0.09 percent, 0.12 percent, and 0.15 percent, respectively. Comparing these findings with a 0.3 percent steel fiber mixture, the obtained CSS values for 0 percent, 0.5 percent, and 0.7 percent of steel fiber are less resistant than the SMA mixture to permanent deformation. The dynamic creep curve revealed a similar result, showing that increasing the value of steel fiber content increases the CSS value for the SMA mixture. The SMA mixture is less resistant to permanent deformation as the CSS value increases [37]. Therefore, it can be concluded that the addition of 0.3 percent of steel fiber is the optimum value for the SMA mixture due to its capability to achieve maximum resistance to permanent deformation.

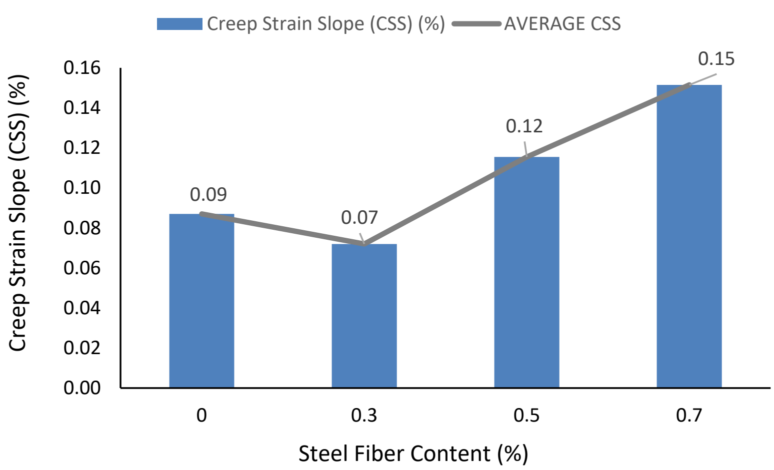

Figure 8. Creep Strain Slope (CSS) of SMA mixture.

3.3. Moisture Susceptibility

Table 5 and Figure 9 demonstrate the unconditioned and moisture conditioned ITS values for Stone Mastic Asphalt (SMA) samples. The ITS values of the conditioned mixes were found to be lower than those of the unconditioned mixtures. This was expected because the decrease in ITS may be attributed to the mixture's loss of adhesion and the asphalt binder's lack of cohesion. This illustrates that the presence of water weakens the mix's structural bonding, decreasing SMA's tensile strength and increasing the chances of the mixture cracking [21,36,38]. The result is consistent with research by Raza et al. [39], where the ITS values of dry samples are higher than conditioned samples. It was expected because water weakens the bonding between the aggregate and binder under loading. The addition of 0.3 percent of steel fiber to a dry condition SMA sample yielded the highest ITS value, followed by 0.5 percent and 0.7 percent, and the control mixture (0 percent) yielded the lowest ITS value. However, the ITS values of the wet condition mixtures followed a different pattern, with the maximum ITS value achieved with 0.3 percent of steel fiber, followed by 0.7 percent, 0.5 percent, and 0 percent. This finding indicates that by adding steel fiber as an additive in SMA, the bond between the aggregate and binder has been improved, thus resulting in greater stiffness. However, the exceeding of steel fiber in the mixtures can increase the viscosity of the asphalt binder, thus limiting the asphalt binder's ability to coat the aggregate sufficiently, thereby causing a very slight possibility of bond failure between the steel fiber, asphalt binder, and aggregates.

Table 5. Moisture Susceptibility.

Steel Fiber Content (Percent)	Sample No.	Indirect Tensile Strength Dry (ITSdry) (kPa)	Indirect Tensile Strength Wet (ITSwet) (kPa)
0	1	308	214
	2	289	236
	3	298	215
0.3	1	358	303
	2	377	399
	3	432	356
0.5	1	335	272
	2	429	315
	3	320	256
0.7	1	369	306
	2	347	296
	3	340	316

Figure 9 shows the TSR values of the asphalt mixtures obtained for the SMA samples. It shows that the TSR values of the modified asphalt mixtures have improved. The performance of moisture susceptibility was improved by up to 22% with 0.3 percent of steel fiber in SMA compared to conventional SMA and other steel fiber proportions. Both mixtures with 0.3 percent and 0.7 percent of steel fiber fulfil the minimum requirement TSR value of 80 percent based on AASHTO T283. The result revealed that the addition of steel fiber reduces the moisture damage of the SMA mix. This finding is similar to the study by Serin S et al. [18], which observed that steel fiber enhances the interconnecting bonds between the asphalt binder, increasing SMA cohesion and adhesion properties. On the other hand, the addition of 0.5 percent of steel fiber and the conventional mixture could not achieve the minimum TSR value, implying that they are more susceptible to moisture damage.

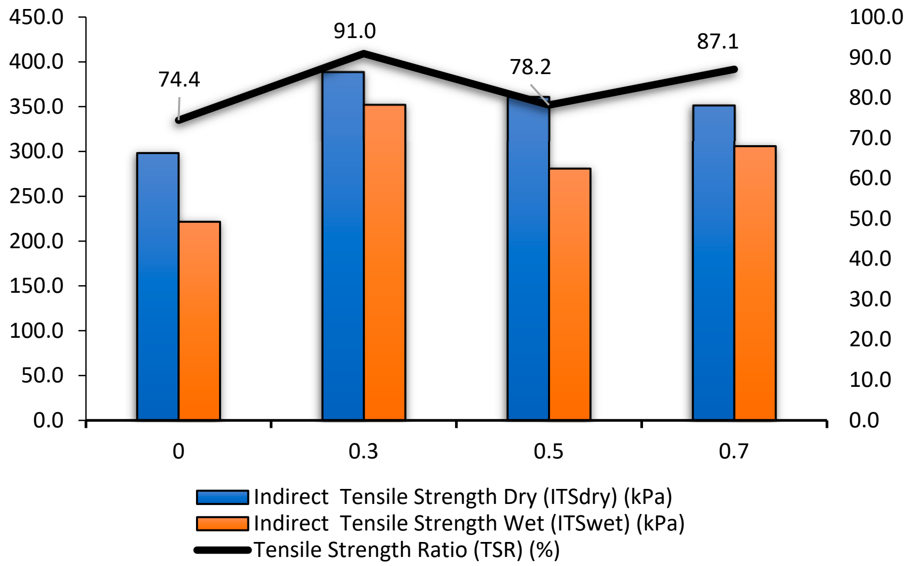

Figure 9. Indirect Tensile Strength (ITS) and Tensile Strength Ratio (TSR).

3.4. Experimental Design Layout

Tables 6 and 7 show the design experiment and responses from the response surface by using software with eight runs for dynamic creep and 12 runs for moisture susceptibility. The alpha used was face-centered with the value of 1 for both experiments and center points of 0 for dynamic creep, meanwhile with 4 for moisture susceptibility.

Table 6. Experimental Design Layout and Result of the Responses for Dynamic Creep.

		Factor 1	Factor 2	Response 1
Std	Run	A: Binder Content	B: Steel Fiber	R1: Creep Strain Slope (CSS)
1	1	5	0	0.082
8	2	6	0.7	0.161
5	3	5	0.5	0.068
2	4	7	0.3	0.06
7	5	6	0	0.092
3	6	5	0.7	0.142
4	7	7	0.5	0.163
6	8	7	0.3	0.096

Table 7. Experimental Design Layout and Result of the Responses for Moisture Susceptibility.

Std		Factor 1	Factor 2	Response 1	Response 2
	Run	A: ITSdry	B: ITSwet	R1: Steel	A: ITSdry
		kPa	kPa	Percent	Percent
6	1	308	214	0	69.481
10	2	289	236	0	81.661
12	3	298	215	0	72.148
4	4	358	303	0.3	84.637
8	5	377	399	0.3	105.836
7	6	432	356	0.3	82.407
2	7	335	272	0.5	81.194
9	8	429	315	0.5	73.427
11	9	320	256	0.5	80
3	10	369	306	0.7	82.927
1	11	347	296	0.7	85.303
5	12	340	316	0.7	92.941

3.5. Effects of One Factor on the Responses

Only one factor is changeable; meanwhile, the rest are kept constant in the one-factor-at-a-time (OFAT) approach. Even though OFAT is not as appropriate as the multiple factors to generate the experiment output because of the interaction only for one factor; but, it can be one of the ways to prove and check the similarity of the data obtained from multiple factors.

3.5.1. Dynamic Creep

The one factor analysis of steel fiber percentage on Creep Strain Slope (CSS) with 95 percent of the confidence interval was set to maximize steel fiber and minimize CSS for optimization. With these criteria of optimization, the software produced the best amount of steel fiber with the highest resistance toward permanent deformation. This was proven by previous research by Jasni et al. [35]; the lower the CSS value, the better the performance of the Stone Mastic Asphalt with additional steel fiber. Therefore, the result produced from the software is 0.25 percent ≈ 0.3 percent for steel fiber with the CSS value of 0.077 percent (Table 8).

Table 8. Optimization for One Factor Analysis on 0.3 percent of Steel Fiber.

Parameter	Steel Fiber (Percent)	Creep Strain Slope (CSS) (Percent)	Tensile Strength Ratio (TSR) (Percent)
Experiment	0.3	0.070	90.58
One Factor	0.3	0.077	89.93
Targeted One Factor	0.3	0.080	90.96

3.5.2. Moisture Susceptibility

The one-factor analysis of steel fiber percentage on Tensile Strength Ratio (TSR) with a 95 percent of confidence interval was set. The temperature and steel binder content was kept constant at 25 °C and six percent. TSR represents the fraction of tensile strength remaining after moisture conditioning and is used to evaluate the moisture susceptibility of asphalt mixtures. The criteria of factor and response are set to maximize for both to ensure that the factor and the response gives the highest performance of the modified asphalt mixture. As required by AASHTO T283, the degree of saturation of SMA samples must be in the range of 70 percent to 80 percent to achieve the saturation value, and it was reported by Shaffie et al. [40] that all sample values must be in the range of 70 percent to 80 percent. Next, as stated in a journal by Khodaii et al. [41], the higher the value of TSR, the better the performance of the modified asphalt. To sum up the output from the one-factor analysis of steel fiber, it was found that the most optimum value of steel fiber is 0.32 percent at 89.93 percent of the tensile strength ratio. Based on AASHTO T283, the value of TSR obtained meets the minimum requirement of 80 percent (Table 8).

3.5.3. Targeted Percentage of Steel Fiber

Based on findings by Shaffie et al. [42], it was found that 0.3 percent is the optimum steel fiber content; therefore, an optimization was done by targeting 0.3 percent of steel fiber and the CSS value was set at a minimum to check the difference in the output from laboratory and statistical experiments. Table 8 shows the CSS value of 0.8 percent when the steel fiber targeted 0.3 percent. Meanwhile, the maximize TSR value was found to be 90.96 percent, also when the steel fiber targeted 0.3 percent.

3.6. Effects of Two Factors on the Responses

The response surfaces were generated based on the experimental design layout. The 3D surface plot is very important to show the interaction between various variables plotted on the x-axis and y-axis.

3.6.1. Dynamic Creep

From the quadratic 3D surface plot with a constant temperature of 25 °C, the CSS value becomes lower as it is approaching 0.3 percent of steel fiber and increases in value again as the number of steel fibers increase. From the 3D plot, it can also be seen that when the factors increase, the CSS value increases (red area). Next, the green area from Figure 10 indicates the area of optimum value of CSS, steel fiber, and binder content. Even so, from Table 9 of optimization for the two factor analysis on 0.3 percent of Steel Fiber, the result of the optimization value of 0.3 percent of steel fiber is a CSS value of 0.075 percent when the binder content is at six percent (optimum binder content from previous research). The criteria of optimization was set to be maximized for steel fiber, minimized for CSS, and targeted for the steel binder, due to the CSS value being less prone to deformation if the value is lower but at the same time, having the best proportion of steel fiber for a better performance of the modified asphalt mixture. Also, the desirability of the ramp of optimization lies almost at 1 with the value of 0.843, which proves that the value of response was given near to the ideal value even though the value was from blue to turquoise.

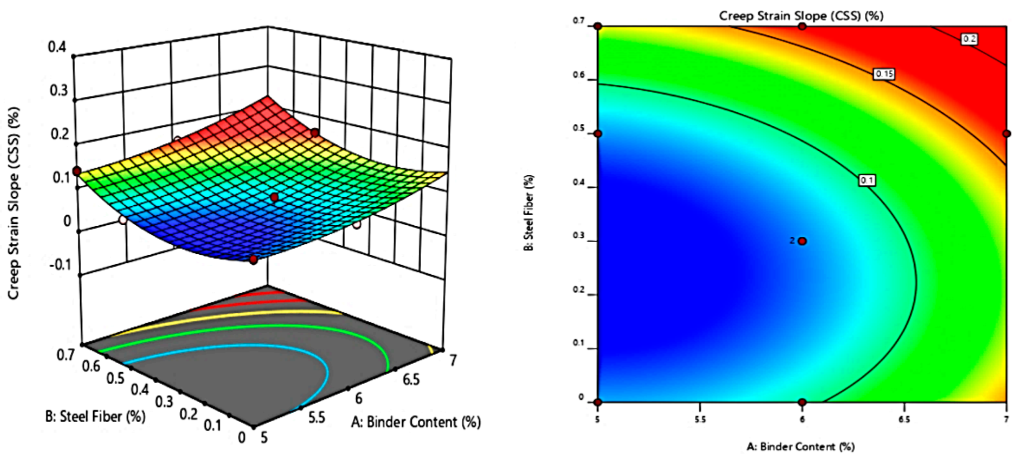

Figure 10. Surface and Contour Plot for Dynamic Creep.

Table 9. Optimization for Two Factor Analysis on 0.3 percent of Steel Fiber.

Parameter	Binder Content (Percent)	Steel Fiber (Percent)	Creep Strain Slope (CSS) (Percent)	Tensile Strength Ratio (TSR) (Percent)
Experiment	6	0.3	0.070	90.58
Two Factor	6	0.3	0.075	91.51
Targeted Two- Factor	6	0.3	0.075	91.32

3.6.2. Moisture Susceptibility

The optimum area is situated at two side areas and the trends show it increasing and becoming critical when one of the factors is at a high value and one is at a lower value (Figure 11). This shows that the additional steel fiber gives an impact on the performance of the modified asphalt mixture. The steel fiber cannot be too big in proportions and cannot be too small (refer to the green area). Meanwhile, by referring to the contour plot (Figure 12), it can be interpreted that the indirect tensile strength dry gives a strong effect on the value of TSR; thus, the presence of water can reduce the strength and performance of a mixture. When one factor is high in value, the other factor is at the lowest value to reach the critical value (red area) of TSR. Next, the higher the TSR value, the better the performance of the asphalt mixture when there is additional steel fiber; thus, the criteria of optimization in Table 9 were set as maximizing for both steel fiber and TSR. The software gives a value of 0.3 percent of steel fiber and 91.51 of TSR as the optimum value if the value is lower but at the same time, has the best percentage of steel fiber.

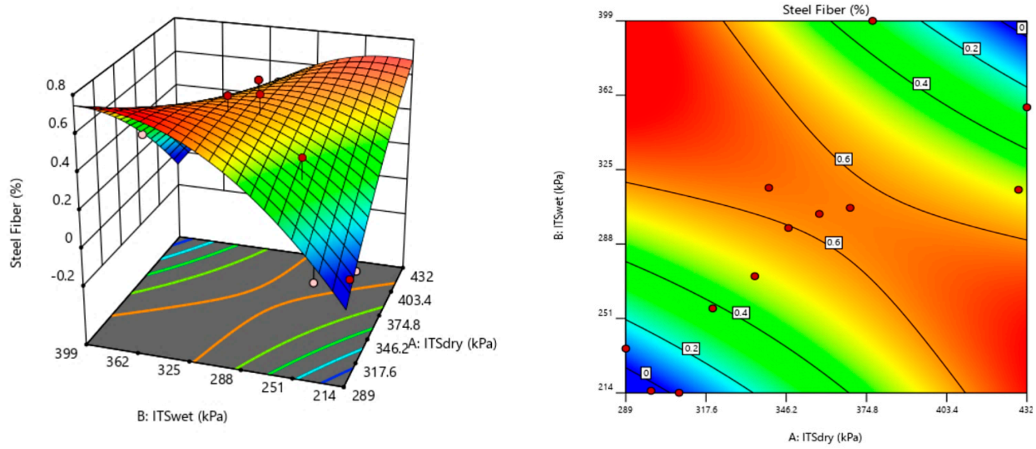

Figure 11. Surface and Contour Plot for Response 1 (Steel Fiber).

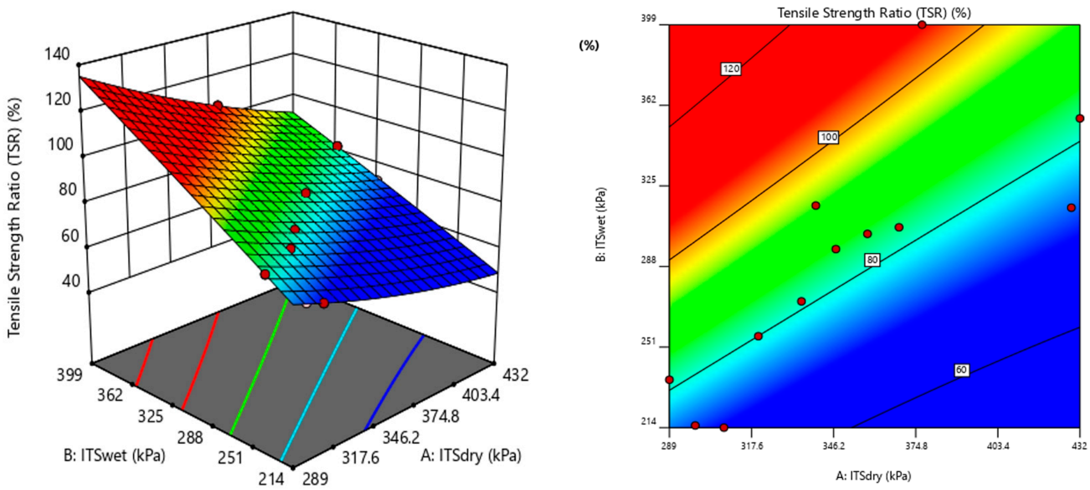

Figure 12. Surface and Contour Plot for Response 2 (TSR).

3.6.3. Targeted Percentage of Steel Fiber

Table 9 depicts the CSS value of 0.075 percent when the steel fiber was targeted at 0.3 percent. Meanwhile, the optimal TSR value was discovered to be 91.32. The optimization was performed by targeting optimum steel fiber content to see if there was any difference in the output.

3.7. Model Fitting

Listed in Table 10 below are the equations used in the software to generate the models. The final equation is in terms of coded factors because the diagnostic and analysis evaluated the factor of 'coded' instead of actual coding. The A, B, and C values represent the factor stated in the ANOVA analysis table.

Table 10. ANOVA for Quadratic Model of Dynamic Creep.

Description	Equation
Dynamic Creep	$0.0789 - 0.0403A + 0.0339B - 0.0059AB - 0.0172A^2 - 0.0515B^2$
Moisture Susceptibility (Steel Fiber)	$0.6145 - 0.0036A + 0.0263B - 0.4050AB - 0.0710A^2 - 0.2323B^2$
Moisture Susceptibility (TSR)	$85.02 - 16.87A + 25.66B - 5.20AB + 3.39A^2 + 0.0932B^2 + 0.5379A^2B + 0.6946AB^2 - 0.5691A^3 - 0.2076B^3$

The model is all significant, which is a good indicator that the model can fit well in the experimental design (Table 11). For dynamic creep, the F-value of 3.34 implies that there is only a 4.8 percent chance that an F-value this large can occur due to noise; meanwhile, moisture susceptibility (steel fiber) only a 3.13 percent chance can occur due to noise with an F-value of 5.43. Thus, the F-value of moisture susceptibility (TSR) is only a 0.01 percent chance to occur due to noise. Next, the p-values of dynamic creep, moisture content (steel fiber), and moisture content (TSR) are less than 0.05. $p < 0.05$ indicates that the model is significant and adequate.

Table 11. ANOVA for Quadratic Model.

Source	Sum of Squares	df	Mean Square	F-Value	*p*-Value	
			Dynamic Creep			
Model	0.0110	5	0.0022	3.34	0.048	significant
A-Binder Content	0.0030	1	0.0030	7.68	0.1093	
B-Steel Fiber	0.0023	1	0.0023	5.95	0.1349	
AB	0.0000	1	0.0000	0.0918	0.7905	
A^2	0.0004	1	0.0004	1.06	0.4122	
B^2	0.0036	1	0.0036	9.33	0.0926	
Residual	0.0008	2	0.0004			
Cor Total	0.0118	7				
			Moisture Susceptibility (Steel Fiber)			
Model	0.6572	5	0.1314	5.43	0.0313	significant
A-ITSdry	9.487×10^{-6}	1	9.487×10^{-6}	0.0004	0.9849	
B-ITSwet	0.0005	1	0.0005	0.0223	0.8861	
AB	0.0109	1	0.0109	0.4510	0.5268	
A^2	0.0013	1	0.0013	0.0520	0.8272	
B^2	0.0162	1	0.0162	0.6693	0.4446	
Residual	0.1453	6	0.0242			
Cor Total	0.8025	11				
			Moisture Susceptibility (TSR)			
Model	1033.51	9	114.83	1.480×10^8	<0.0001	significant
A-ITSdry	4.31	1	4.31	5.549×10^6	<0.0001	
B-ITSwet	3.50	1	3.50	4.514×10^6	<0.0001	
AB	0.0286	1	0.0286	36,841.10	<0.0001	
A^2	0.0336	1	0.0336	43,312.45	<0.0001	
B^2	0.0002	1	0.0002	217.96	0.0046	
A^2B	0.0000	1	0.0000	29.35	0.0324	
AB^2	0.0000	1	0.0000	36.00	0.0267	
A^3	0.0003	1	0.0003	408.39	0.0024	
B^3	0.0000	1	0.0000	29.32	0.0325	
Residual	1.552×10^{-6}	2	7.759×10^{-7}			
Cor Total	1033.51	11				

As for fit statistics, a value of R^2 more than 0.8 shows that the value is acceptable. Table 12 shows the value exceeds 0.8 and can be considered close to 1.0, which indicates that the model is significant and adequate. For negative adjusted R^2, it indicates that the overall mean can be a better predictor of the response than the current model but in some cases, a higher order can also predict better. In different cases of moisture susceptibility (TSR), 0.9999 is in reasonable agreement with the adjusted R^2. Lastly, for the measurement of the signal-of-noise ratio, it is indicated by the Adeq Precision to navigate the design space [31]. Adeq Precision > 4 is another indicator to show that the model is adequate.

Table 12. Fit Statistic for Quadratic Model.

Parameter	Dynamic Creep	Moisture Susceptibility (Steel Fiber)	Moisture Susceptibility (TSR)
Std. Dev.	0.0197	0.1556	0.0009
Mean	0.1083	0.3750	82.66
C.V. percent	18.21	41.50	0.0011
R^2	0.9340	0.8189	1.0000
Adjusted R^2	0.7691	0.6679	1.0000
Predicted R^2	−0.3247	−1.1317	0.9999
Adeq Precision	5.2253	6.0149	45,212.9481

3.8. Comparison between Laboratory and Statistical Experiment

Table 13 shows the difference and similarity of the value obtained from laboratory experiments and statistical experiments by using the response surface of one and two factors of analysis. The method of experiment has a significant effect on the value reported for experimental design. A 0.3 percent targeted steel fiber value was chosen to observe the similarity in the value of the responses with the software output as 0.3 percent being the optimum steel fiber content obtained in the laboratory experiment. Based on the criteria and statistical experiment by Response Surface Methodology (RSM), the optimal condition was obtained. According to this table, the difference between the laboratory experiment and four statistical experiments is too small for the responses and the steel fiber value is the same without using the targeted value. Therefore, it shows that the optimum steel fiber content obtained from laboratory experiments and statistical experiments has a good precision in both individual and interaction factors of analysis. Thus, a 0.3 percent addition of steel fiber in asphalt mixture can be accepted.

Table 13. Optimum Statistical and Laboratory Experiment Value.

Description	Steel Fiber %	Creep Strain Slope (CSS)%	Tensile Strength Ratio (TSR)%
Laboratory Experiment	0.3	0.07	90.58
Statistical (One factor)	$0.25 \approx 0.3$	0.077	-
	$0.32 \approx 0.3$	-	89.93
Difference	0	0.007	0.65
Percentage Difference (percent)	0	9	0.07
Statistical (Targeted one factor)	0.3	0.08	-
	0.3	-	90.96
Difference	N/A	0.01	0.38
Percentage Difference (percent)	N/A	12.5	0.42
Statistical (Two factor)	0.3	0.075	-
Residual	$0.31 \approx 0.3$	-	91.505
Difference	0	0.005	0.925
Percentage Difference (percent)	0	7.14	1.01
Statistical (Targeted Two factor)	0.3	0.075	-
	0.3	-	91.32
Difference	N/A	0.005	0.74
Percentage Difference (percent)	N/A	7.14	0.08

4. Conclusions

The use of steel fiber in asphalt pavements has recently been the subject of some investigation. This research aimed to determine the optimum amount of steel fiber in a modified asphalt mixture and characterize the performance of steel fiber in the SMA mixture. A statistical analysis of Response Surface Methodology (RSM) was used in this investigation to find the interaction between selected variables. A few conclusions and recommendations can be drawn based on the results obtained from the optimization of the content of steel fiber in a modified asphalt mixture of SMA:

- It can be indicated that the incorporation of steel fiber in the asphalt mixture increases the stability compared to the conventional mixture. In the meantime, the flow values go through reduction. In relation to these indications, it can be said that the optimum percentage of steel fiber to be utilized in the SMA mixture in terms of stability is 0.3 percent.

- Experimental results from the dynamic creep and moisture susceptibility have shown that the addition of steel fiber into the asphalt mixture improves the SMA mixture performance. Comparing the result with conventional and different proportions of steel fiber, 0.3 percent of steel fiber in SMA showed the greatest improvement in terms of permanent deformation. The addition of 0.3 percent of steel fiber to the mix decreases the strain value considerably as compared to the control mix. This means that the SMA mixture with 0.3 percent of steel fiber is resistant to permanent deformation. In addition, steel fiber in SMA strengthened the bonding between the aggregate and binder, resulting in increased stiffness. It was also revealed that the indirect tensile strength, and also TSR ratio, peaked at 0.3 percent of steel fiber content. It is proved that the presence of steel fiber reduces moisture-induced damage or stripping potential of SMA compared to the conventional mixture. This indicates that steel fiber strengthens the interconnecting bonds between the bitumen molecules, enhancing the cohesion and adhesion properties of SMA when being exposed to moisture.
- The research revealed that the Response Surface Methodology (RSM) is an effective statistical method for providing an appropriate empirical model for relating parameters and predicting the optimum performance of asphaltic mixture to reduce flexible pavement failure. RSM is proven to be one of the efficient ways of an experiment; not only does it save cost and time but it can also give similar results to the laboratory result. From one-factor and two-factor analysis, it was found in one and multiple interactions that the value of relative error is still small, and the percentage difference is less than 15 percent from laboratory results which indicates that the model is fitted with the experiment. An amount of 0.3 percent was found to be the most optimum steel fiber content from the optimization by using Response Surface Methodology, which thus proves that additional steel fiber in the SMA mixture enhanced the performance of the mixture.
- Future research on the dynamic creep performance with three different temperatures should be conducted to check the suitability of the steel fiber-modified SMA mixture due to the various weather conditions, and should conduct a laboratory experiment along with the statistical experiment in research based on the value from software.

Author Contributions: E.S.: Supervision, Conceptualization, Writing—Original draft. A.A.M.N.: Methodology, Investigation, Formal analysis. R.P.J.: Supervision, Reviewing, Funding acquisition. A.K.A.: Writing, Reviewing, Data curation. N.M.R.: Formal analysis, Reviewing. Z.H.A.-S.; Reviewing, Editing. All authors have read and agreed to the published version of the manuscript.

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References

1. Darma, Y.; Karim, M.R.; Abdullah, S. An analysis of Malaysia road traffic death distribution by road environment. *Sadhana—Acad. Proc. Eng. Sci.* **2017**, *42*, 1605–1615. [CrossRef]
2. Sengul, C.E.; Oruc, S.; Iskender, E.; Aksoy, A. Evaluation of SBS modified stone mastic asphalt pavement performance. *Constr. Build. Mater.* **2013**, *41*, 777–783. [CrossRef]
3. Bindu, C.S. Influence of Additives on the Characteristics of Stone Matrix Asphalt. Ph.D. Thesis, Cochin University of Science and Technology, Kochi, India, 2012.
4. Mokhtari, A.; Nejad, F.M. Mechanistic approach for fiber and polymer modified SMA mixtures. *Constr. Build. Mater.* **2012**, *36*, 381–390. [CrossRef]
5. Sarang, G.; Lekha, B.; Krishna, G.; Shankar, A.R. Comparison of Stone Matrix Asphalt mixtures with polymer-modified bitumen and shredded waste plastics. *Road Mater. Pavement Des.* **2015**, *17*, 933–945. [CrossRef]
6. Ibrahim, A.N.H.; Ahmad, A.S.; Akhir, N.M.; Borhan, M.N. Performance evaluation of Stone Mastic Asphalt (SMA) using geopolymer as an asphalt modifier. *Jordan J. Civ. Eng.* **2016**, *10*, 442–450.
7. Punith, V.S.; Veeraragavan, A. Behavior of Reclaimed Polyethylene Modified Asphalt Cement for Paving Purposes. *J. Mater. Civ. Eng.* **2010**, *23*, 833–845. [CrossRef]
8. Maurer, D.A.; Malasheskie, G.J. Field performance of fabrics and fibers to retard reflective cracking. *Geotext. Geomembr.* **1989**, *8*, 239–267. [CrossRef]
9. Hassan, H.F.; Oraimi, S.A.; Taha, A. Evaluation of open-graded friction course mixtures containing cellulose fibers and styrene butadiene rubber polymer. *J. Mater Civil. Eng.* **2005**, *17*, 416–422. [CrossRef]
10. Serfass, J.P.; Samanos, J. Fiber-modified asphalt concrete characteristics, applications and behavior. *J. Assoc. Asphalt. Paving. Technol.* **1996**, *64*, 193–230.
11. Wu, S.; Ye, Q.; Li, N.; Yue, H. Effects of fibers on the dynamic properties of asphalt mixtures. *J. Wuhan Univ. Technol. Sci. Ed.* **2007**, *22*, 733–736. [CrossRef]
12. Putman, B.J.; Amirkhanian, S.N. Utilization of waste fibers in stone matrix asphalt mixtures. *Resour. Conserv. Recycl.* **2004**, *42*, 265–274. [CrossRef]
13. McDaniel, R.S. Asphalt Additives to Control Rutting and Cracking. Ph.D. Thesis, Purdue University, West Lafayette, IN, USA, 2001.
14. Chen, H.; Li, N.; Hu, C.; Zhang, Z. Mechanical performance of fibers-reinforced asphalt mixture. *J. Chang'an Univ. (Nat. Sci. Ed.)* **2004**, *24*, 1–5.
15. Tapkın, S. The effect of polypropylene fibers on asphalt performance. *Build. Environ.* **2008**, *43*, 1065–1071. [CrossRef]
16. Chen, H.; Xu, Q.; Chen, S.; Zhang, Z. Evaluation and design of fiber-reinforced asphalt mixtures. *Mater. Des.* **2009**, *30*, 2595–2603. [CrossRef]
17. Al-Bdairi, A.; Al-Taweel, H.M.; Noor, H.M. Improving the properties of asphalt mixture using fiber materials. *IOP Conf. Series: Mater. Sci. Eng.* **2020**, *870*, 012092. [CrossRef]
18. Serin, S.; Morova, N.; Saltan, M.; Terzi, S. Investigation of usability of steel fibers in asphalt concrete mixtures. *Constr. Build. Mater.* **2012**, *36*, 238–244. [CrossRef]
19. Putman, B.J. Effects of Fiber Finish on the Performance of Asphalt Binders and Mastics. *Adv. Civ. Eng.* **2011**, *2011*, 172634. [CrossRef]
20. Shaffie, E.; Ahmad, J.; Arshad, A.K.; Kamarun, D. Evaluation Of Volumetric Properties And Resilient Modulus Performance Of Nanopolyacrylate Polymer Modified Binder (NPMB) Asphalt Mixes. *J. Teknol.* **2015**, *73*, 21–25. [CrossRef]
21. Sarsam, S.I. Comparative evaluation of moisture susceptibility for Porous And Stone Matrix Asphalt concrete. *Indian J. Eng.* **2021**, *18*, 424–432.
22. AL-Ridha, A.S.; Ibrahim, A.L.S.K.; Dheyab, E.L.S. Steel fiber effect on the behavior of hot mixture asphalt with variable asphalt content. *Int. J. Adv. Technol. Eng. Sci.* **2016**, *4*, 204–213.
23. AL-Ridha, A.S.; Ali, K.I.; Hayder, M.A.T.; Layth, S.D. Effect of steel fiber on ultrasonic pulse velocity and mechanical properties of self-compact light weight concrete. *IOP Conf. Ser. Mater. Sci. Eng.* **2019**, *518*, 022017. [CrossRef]
24. Al-Ridha, A.S.D.; Abbood, A.A.; Atshan, A.F. Assessment of the Effect of Replacing Normal Aggregate by Porcelinite on the Behaviour of Layered Steel Fibrous Self-Compacting Reinforced Concrete Slabs under Uniform Load. *J. Eng.* **2020**, *2020*, 3650363. [CrossRef]
25. Al-Sarraf, D.S.; Al-Shaarbaf, D.I.; Diab, D.A. Effect of steel fiber on the behavior of deep beams with and without web Opening. *Eng. Technol.* **2011**, *29*, 1–19.
26. Ahmed, S.D.; Ridha, A.L. The influence of size of lightweight aggregate on the mechanical properties of self-compacting concrete with and without steel fiber. *Int. J. Struct. Civ. Eng. Res.* **2014**, *3*, 54–68.
27. Ahmed, L.S.A.; Mahmood, L.O.T. Influence of Mineral Fibers Properties on the Performance of Hot Mix Asphalt for the Surface Layer of Pavement. *Int. J. Eng. Trends Technol.* **2015**, *26*, 145–151. [CrossRef]
28. Kikuchi, S.; Kronprasert, N.; Easa, S.M. Aggregate blending using fuzzy optimization. *J. Constr. Eng. Manag.* **2012**, *138*, 1411–1420. [CrossRef]
29. Tharazi, I.; Sulong, A.B.; Salleh, F.M.; Abdullah, A.H.; Ismail, N.F. Application of response surface methodology for parameters optimization in hot pressing kenaf reinforced biocomposites. *J. Mech. Eng.* **2020**, *17*, 131–144. [CrossRef]

30. Nassar, A.I.; Thom, N.; Parry, T. Optimizing the mix design of cold asphalt binder emulsion mixtures using response surface methodology. *Constr. Build. Mater.* **2016**, *104*, 216–229. [CrossRef]
31. Soltani, M.; Moghaddam, T.B.; Karim, M.R.; Baaj, H. Analysis of fatigue properties of unmodified and polyethylene terephthalate modified asphalt mixtures using response surface methodology. *Eng. Fail. Anal.* **2015**, *58*, 238–248. [CrossRef]
32. *JKR/SPJ/S4*; Standard Specification for Road Works. Public Works Department: Kuala Lumpur, Malaysia, 2008.
33. *EN 12697-25*; Bituminous Mixtures Test Methods: Cyclic Compression Test. European Committee for Standardization: Brussels, Belgium, 2016.
34. *AASHTO T283-07*; Resistance of compacted Hot Mix Asphalt (HMA) to Mixture-Induced Damage. American Association of State Highway and Transportation Officials (AASHTO): Washington, DC, USA, 2008.
35. Jasni, N.E.; A Masri, K.; Ramadhansyah, P.J.; Arshad, A.K.; Shaffie, E.; Ahmad, J.; Norhidayah, A.H. Mechanical Performance of Stone Mastic Asphalt Incorporating Steel Fiber. *IOP Conf. Series: Mater. Sci. Eng.* **2020**, *712*, 012026. [CrossRef]
36. Moghaddam, T.B.; Soltani, M.; Karim, M.R. Evaluation of permanent deformation characteristics of unmodified and polyethylene terephthalate modified asphalt mixtures using dynamic creep test. *Mater. Des.* **2014**, *53*, 317–324. [CrossRef]
37. Katman, H.Y.; Ibrahim, M.R.; Karim, M.R.; Mashaan, N.S.; Koting, S. Evaluation of Permanent Deformation of Unmodified and Rubber-Reinforced SMA Asphalt Mixtures Using Dynamic Creep Test. *Adv. Mater. Sci. Eng.* **2015**, *2015*, 247149. [CrossRef]
38. Gilani, V.N.M.; Hamedi, G.H.; Esmaeeli, M.R.; Habibzadeh, M.; Eshkiknezhad, M.H. Presentation of thermodynamic and dynamic modules methods to investigate the effect of nano hydrated lime on moisture damage of stone matrix asphalt. *Aust. J. Civ. Eng.* **2022**. [CrossRef]
39. Raza, A.; Khan, I.; Tufail, R.F.; Frankovska, J.; Mushtaq, M.U.; Salmi, A.; Awad, Y.A.; Javed, M.F. Evaluation of moisture damage potential in hot mix asphalt using polymeric aggregate treatment. *Materials* **2022**, *15*, 5437. [CrossRef] [PubMed]
40. Shaffie, E.; Rashid, H.A.; Shiong, F.; Arshad, A.K.; Ahmad, J.; Hashim, W.; Putra Jaya, R.; Masri, K.A. Performance characterization of Stone Mastic Asphalt using steel fiber. *J. Adv. Ind. Technol. Appl.* **2021**, *2*, 22–33. [CrossRef]
41. Khodaii, A.; Haghshenas, H.F.; Tehrani, H.K.; Khedmati, M. Application of response surface methodology to evaluate stone matrix asphalt stripping potential. *KSCE J. Civ. Eng.* **2013**, *17*, 117–121. [CrossRef]
42. Shaffie, E.; Ahmad, H.E.; Arshad, A.K.; Hashim, W.; Yaacob, H.; Shiong, F. Performance evaluation of stone mastic asphalt containing steel fiber as additive. In *Green Infrastructure*; Springer: Singapore, 2022. [CrossRef]