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Performance Characterization of Stone Mastic Asphalt using Steel Fiber

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Abstract: Stone Mastic Asphalt (SMA) is a gap-graded hot mixture designed to provide higher resistance towards permanent deformation and rutting potential by 30% to 40% more than dense-graded asphalt, due to its stable aggregate skeleton structure. However, compared to other types of hot mix asphalt, SMA unfortunately has some shortcomings in term of its susceptibility towards moisture-induced damage due to its structure and excessive bitumen content in the composition. This research aims to assess the performance of a SMA mixture with steel fiber by enhancing overall stability, abrasion resistance, and, most importantly, moisture susceptibility. This study involved the incorporation of various steel fiber proportions of 0%, 0.3%, 0.5% and 0.7% by the total weight of mixture. The steel fiber modified SMA was made up of 6.0% PEN 60/70 bitumen content. The performance of SMA were evaluated through Marshall stability and flow test, Cantabro loss test and indirect tensile strength test. The results obtained from the testing showed that the incorporation of steel fiber is significantly effective to enhance the resistance towards moisture damage, while increasing the stability and reducing the abrasion loss of SMA mixture, compared to conventional mixture. Overall, it can be concluded that the addition of steel fiber in asphalt mixture specifically SMA, has improved the mechanical performance in the application of asphalt pavement with the optimum steel fiber proportion of 0.3% by the weight of mixture. The developed models between the independent variables and responses demonstrated high levels of correlation. The study found that Response Surface Methodology (RSM) is an effective statistical method for providing an appropriate empirical model for relating parameters and predicting the optimum performance of an asphaltic mixture to reduce flexible pavement failure.

Keywords: Stone Mastic Asphalt, modified SMA, steel fiber, moisture susceptibility

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1. Introduction

Due to the rapid urbanization of the world over the last century, the construction and maintenance of transportation roadways is a constant demand in both urban and rural areas. The design of asphalt mixture composition involves the suitable selection and proportioning of materials to achieve the desired properties of the end results in the application of road pavement to eliminate pavement deterioration. Stone Mastic Asphalt (SMA) which is of a gap-graded hot mixture is designed to provide high resistance towards permanent deformation and rutting potential due to its stable aggregate skeleton structure [1]. Most of the previous studies have proved that SMA can sustain heavy traffic conditions, but its application is very limited mainly due to the lack of proper specifications.

Moisture effects have been reported as one of the leading causes of asphalt mixture deterioration, which leads to the breakdown of road structures and causes pavement distress such as stripping, ravelling, rutting, and potholes [2]. Moisture damage has been known to be related to the problem of adhesion loss between bitumen and aggregates or within the asphalt binder itself, which are weakened in the presence of water. Environmental conditions including humidity, precipitation, and temperature variations have constantly degrade the material properties and eventually affects pavement performance. Due to these, the overall service life of road pavement has somehow reduced, especially on the utilization of conventional asphalt mixture, which have led to the increase of maintenance expenditure [3]. Stone Mastic Asphalt (SMA) is more sensitive and susceptible to moisture damage compared to other types of hot mix asphalt, due to its gap-graded structure and excessive bitumen content in the composition. When asphalt mixture is too sensitive towards moisture, it easily affects the stripping potential of the road pavement. Water can penetrate via cracks on the surface of the pavement that may cause the loss of adhesion between bitumen and aggregate. This leads to the occurrence of surface cracks which eventually contributes to more severe road problem, such as potholes [4].

Modified asphalt mixture is important to ensure the maximum performance and strength of road pavement can be achieved, with regards to the durability and long service life of the pavement. Hence, the modification of SMA is highly convenient to enhance the moisture resistance and durability of the mixture. In dealing with pavement distresses, one of the many alternative materials that has been proven of the positive contribution towards improving asphalt mixtures' stability and resistance against moisture damage is the utilization of fibers. Fiber is a type of polymer that is commonly used as an addition for this purpose [5]. The addition of fibers changes the viscoelasticity of the mixture [6], increases its dynamic modulus [7], improves humidity sensitivity [8], and improves flow coherence, and provides rutting resistance [9, 10]. According to the study done by Serin [6], the use of fibers can provide strengthening effect to the application of road pavement. The utilization of fibers plays a remarkable role in gap-graded mixture as it enhances the stability and sensibility against humidity.

Fibers commonly used in asphalt mixture are synthetic fibers, glass fibers, natural fibers, and steel fibers. Since the advent of fiber modified asphalt mixture, a great deal of testing has been conducted on various fibrous materials to determine the actual characteristics and advantages for each type. However, due to its good mechanical properties, low water absorption, and high melting point, a new environmentally friendly fibre, steel fiber, has attracted a lot of attention [7]. The main objective of this study is to evaluate the performance of modified SMA with steel fiber by using Marshall compaction methods. Physical properties, volumetric properties, and pavement performance of modified SMA with steel fiber were also studied to compare and analyse the utilization of steel fiber can improve the mechanical performance as an improvement for conventional SMA to contribute to the field of transportation and highway development.

2. Methodology

2.1 Aggregate Properties

Granite aggregates were used in asphalt mixtures. These aggregates were sourced from Kajang Rocks Quarry. The aggregates have been dried and sieved into a selected size range with nominal size 20 mm as per JKR Malaysia's specification requirements of SMA20. Aggregate material tests were carried out based on ASTM standard procedure, to obtain the physical and mechanical characteristics of the materials to be used in the mixtures. Aggregate gradation for SMA mixture has been chosen as shown in Table 1.

Table 1 - SMA gradation

Sieve size (mm)	Passing (%)	Gradation Limit (%)
12.5	100	100
9.5	77.5	72-83
4.75	31.5	25-38
2.36	20.0	16-24
0.6	14.0	12-16
0.3	13.5	12-15
0.075	9.0	8-10

Penetration Grade (PEN 60/70) asphalt binder was used in asphalt mixtures as bitumen. In this study, Steel fiber as shown in Fig. 1 was used. Steel fibre from Gardner Global Enterprise was used to make a proportion as an addition to SMA with various percentages of 0%, 0.30%, 0.50%, and 0.70% by total weight of mixture. The properties of steel fibers are shown in Tables 2.

Fig. 1 - Steel fiber

Table 2 - Properties of steel fibers

Description	Length (mm)	Diameter (mm)	Density (Kg/m^3)	Tensile Strength (Mpa)	Aspect Ratio
Straight	13	0.2	7800	2600	65

2.2 Marshall Mix Design

A total number of twelve (12) Marshall samples were prepared in accordance with ASTM D 1559. For the preparation of SMA mixtures, 1100 g of mixed aggregate and filler were heated with a temperature range of 160°C. The required quantity of bitumen was heated to a temperature of 160°C (mixing temperature) to achieve desirable viscosity for preparation of mixture. The bitumen content used was 6% by the weight of mixture, adopted by the previous study [8]. As a method of dry blending method process, the steel fiber (0%, 0.3%, 0.5% and 0.7%) by the total weight of mixture were added directly to the mixture before the bitumen. All test samples were subjected to 50 blows per face by standard Marshall compactor. All twelve (12) Marshall samples were used for further evaluation on Marshall stability and flow test and Cantabro test in accordance with the specific standards. The process of Marshall stability test is shown in Fig. 2.

a) Marshall stability test b) Sample position machine

Fig. 2 - Marshall stability test

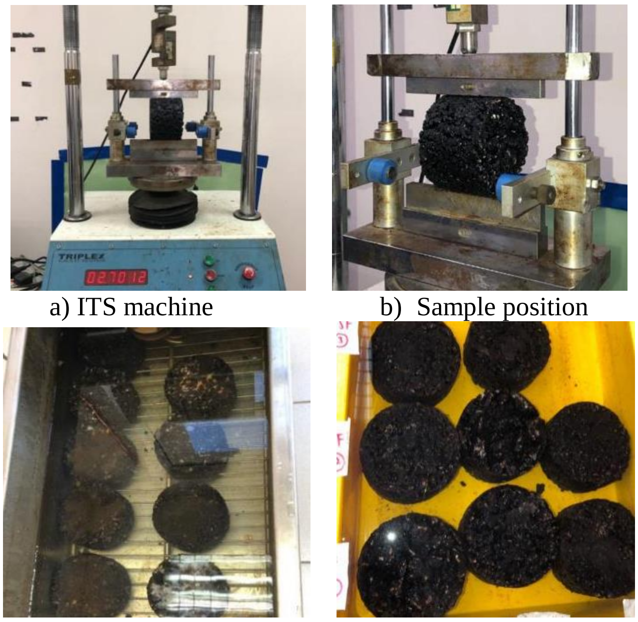
2.3 Cantabro Loss Test

Cantabro loss test was carried out in this study to assess on mixture toughness and abrasion characteristics in order to come up with the best quality of SMA with an optimum proportion of steel fiber as additives. This test was conducted to evaluate the ability of asphalt mixture to withstand degradation by estimating the percentage of loss in the compacted SMA samples by using Los Angeles Abrasion machine (Fig. 3) without steel ball. This test was conducted according to ASTM D 7064 on twelve (12) test samples. The samples were kept at a temperature of 25ºC for six hours, before being recorded of their masses as the initial mass of sample before testing and placed into the machine. The drum was subjected to 300 revolutions at a velocity between 188 and 208 rad/s. After reaching 300 revolutions, the test samples were weighed as the final mass, without including any discarded loose materials coming off from the SMA samples.

Fig. 3 - Los Angeles abrasion machine

2.4 Moisture Susceptibility Test

The investigation of SMA moisture susceptibility was carried out on a total of 24 test samples using an Indirect Tensile Strength (ITS) test under wet and dry conditions. The test samples were condition, and the Indirect Tensile Strength (ITS) test were carried out according to the procedure described in AASHTO T 283. For each percentage of steel fibre content, three (3) compacted samples were prepared in dry conditions and three (3) compacted samples in wet conditions. Prior to testing the ITSdry, all unconditioned samples for each steel fibre percentage were left at room temperature of 25°C for 24 hours. The other conditioned samples were immersed in a 60°C water bath for 24 hours, then in 25°C water for 2 hours and 10 minutes before being tested for ITSwet. ITS test was performed by loading the samples at a constant rate and measuring the force required to break the sample. Samples were placed on its side between the bearing plates of the ITS machine. Steel loading strips were placed between the sample and the bearing plates and proceeded with loading the samples at a constant head rate of 50 mm/minute vertical deformation at 25°C. The stripping potential for the asphalt mixture was evaluated based on Tensile Strength Ratio (TSR) which was obtained through the ratio of the average of tensile strength of the conditioned subset to the average tensile strength of the dry subset. This overall procedure of moisture susceptibility test is shown in Fig. 4 (a-d).



a) ITS machine b) Sample position

c) Wet subsets d) Dry subsets

Fig. 4 - Moisture susceptibility test

2.5 Response Surface Methodology

The Response Surface Method (RSM) is a method for decrease the quantity of experimental or simulation data required to characterise a system. The “response” is the term used to describe the dependent variable of interest. RSM depicts the impact of various independent variables on the responses. RSM for regression and graphical analyses of the collected data was performed using Design Expert software Version 11.0.5. In this study, historical data design was chosen to determine an approximate function between variables and response. The user can define the design points for this design based on the current experimental data. To develop an interaction, this design was used to evaluate the relationship between three variables and one response. Steel fibre content, ITS wet and ITS dry are the variables, and TSR is the response.

3. Results and Discussion

3.1 Stability and Flow Test

The Marshall stability values for all SMA mixtures with different steel fiber proportions are shown in Fig. 5. It is shown that the stability increased initially, reached a maximum value, and then started to show a decrement with the increasing proportion of steel fiber. In comparison to other percentages, 0.3 percent steel fiber in SMA produced the highest stability, with a stability improvement of up to 23% over control SMA. This is due to the small amount of steel fiber in the mix, which contributes to a high level of stability because of the contact points between the aggregates. On the contrary, the stability values started to reveal a gradual decrease with 0.5% and 0.7% steel fiber. This pattern is similar to the findings of Jasni et al. (2020), who discovered that stability increases with low steel fiber content and decreases with increased fiber content [9]. This occurs due to the excessive amount of steel fiber that may not disperse uniformly and eventually form weak points within the mixture because of coagulation. However, the addition of 0.5% and 0.7% steel fibre still showed stability improvement of up to 21% and 12% respectively, compared to the control SMA which shows the lowest maximum load amongst all steel fiber proportions. Stability increase can be attributed to improve adhesion between the aggregate and bitumen. This indicates that the addition of steel fiber in asphalt mixture specifically SMA, enhances rutting resistance and achieve better performance than plain mixture. This finding is consistent with several studies done by previous researchers which proved that the use of steel fiber in asphalt mixture contributes to better stability performance, compared to conventional mixture [6], [10], [11].

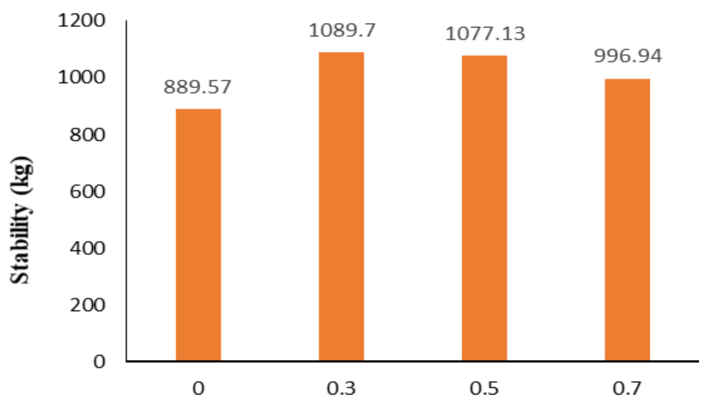


Fig. 5 - Stability values with different steel fibre content

The flow values for SMA mixtures with various proportions of steel fiber as additives are shown in Fig. 6. The flow value was used to assess the flexibility of mixtures. By investigating each flow value obtained for 0%, 0.30%, 0.50%, and 0.70% steel fiber, the flow value tends to decrease slightly with increasing steel fiber content. The highest flow value was reported by the control SMA, while the lowest flow value was recorded by the mixture of 0.7% steel fiber. Steel fiber content of 0.3 percent, 0.5 percent, and 0.7 percent reduces flow values by approximately 22 percent, 25 percent, and 29 percent, respectively. The results reveal that increasing the amount of steel fiber in the asphalt mixture reduces flow values due to the stiffness of the steel fibers in the mixture, resulting in a less flexible combination. This is supported by N. E. Jasni et al., [9], indicated that with increasing amounts of steel fiber, flow values decreased and thus concluded that the mixture became less flexible owing to the stiffness of fibers.

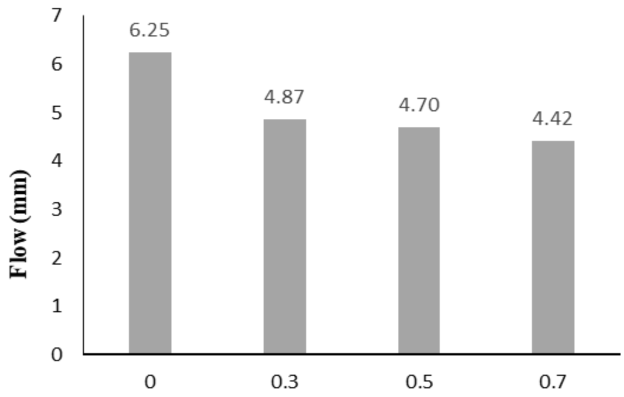


Fig. 6 - Flow values with different steel fiber content

3.2 Cantabro Loss Test

According to the Cantabro loss values shown in Fig. 7, the SMA mixture with 0.3 percent steel fibre content had the lowest abrasion loss percentage of 5.95 percent, followed by 0.5 percent, 0 percent, and 0.7 percent steel fibre. In contrast to the other proportions, the SMA mixture with 0.7 percent steel fiber had the highest Cantabro loss of 6.82 percent. The differences in abrasion loss revealed by each proportion are due to the abrasion force between the mixture specimens and drum, which causes the mixture to be disintegrated with certain amount of abrasion loss. It can be observed that the abrasion loss significantly reduced by up to 13 percent with the incorporation of 0.3 percent , however following the addition of 0.5 percent and 0.7 percent steel fiber to the SMA mixture, the abrasion loss increased. The abrasion loss value of the control mixture is found to be up to 0.7 percent higher when 0.7 percent steel fiber is added. This indicates that increasing the proportion of steel fiber in a SMA mixture does not improve its abrasion resistance, which is consistent with other researcher findings [7]. Variations in abrasion values, on the other hand, could be caused by a variety of factors, including the angularity of coarse aggregates and uneven compaction force. In general, it has been showed that the effects of adding steel fiber to SMA in reducing abrasion loss is effective when appropriate proportions are used.

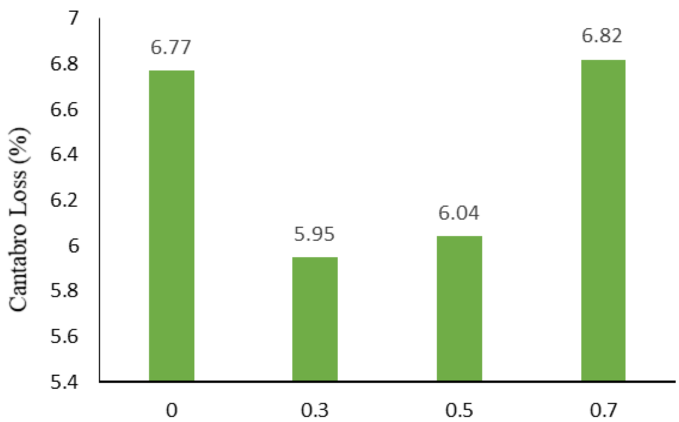


Fig. 7 - Cantabro loss values with different steel fiber content

3.3 Indirect Tensile Strength Test

Fig. 8 shows the Indirect Tensile Strength (ITS) obtained for SMA samples. Based on the comparison of ITS values for both dry and wet SMA samples, it can be interpreted that the indirect tensile strength of wet condition samples was significantly lower than that of dry condition samples for every steel fiber proportion. This shows that the presence of water can reduce the tensile strength of SMA, thus exposing the mixture to a bigger potential of cracking [12]. It is shown that the highest ITS value for dry condition SMA sample was with the addition of 0.3% steel fiber, followed by 0.5%, 0.7% and the lowest ITS value exhibited by the conventional mixture. A different trend was seen on the ITS values of wet condition mixture, where the highest ITS value was obtained with 0.3% steel fiber, followed by 0.7%, 0.5% and 0%. As a result, using steel fibre as an additive in SMA has strengthened the bonding between the aggregate and binder, resulting in increased stiffness. It was also revealed that the indirect tensile strength peaked at 0.3 percent steel fiber content and then decreased as the steel fiber content increased. One possible reason for this phenomenon is the presence of steel fiber in the mixture, which can stiffen the mixture. This explanation is similar to those describe by Serin S et al. [6] and D Al-Ridha et al. [10], the addition of steel fiber that exceeds a certain level can increase the viscosity of the bitumen, which can restrain the ability of bitumen to coat adequately on aggregates, thereby leading to a slight potential of bonding loss between steel fiber, bitumen, and aggregates.

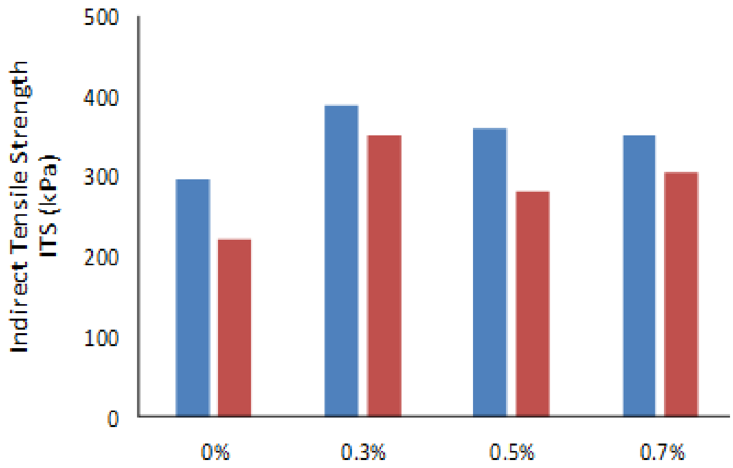


Fig. 8 - Indirect Tensile Strength (ITS) with different steel fiber content

Fig. 9 shows the values of Tensile Strength Ratio (TSR) obtained for the SMA samples. TSR value is an indicator of moisture damage potential of a mixture, obtained from the ratio of ITS_{wet} to ITS_{dry}. It is revealed that 0.3% steel fiber in SMA exhibited the highest improvement regarding moisture susceptibility performance by up to 22% compared to the conventional SMA and other steel fiber proportions. TSR values of mixtures with 0.3% and 0.7% steel fiber achieved higher values than the minimum requirement of 80% based on AASHTO T 283. In contrast, the incorporation of 0.5% steel fiber did not reach the minimum TSR value, similar to the control mixture with 0% steel fiber, which can be interpreted that they are more sensitive towards moisture damage [6]. However, from these results, it is proved that the presence of steel fiber reduces moisture-induced damage or stripping potential of SMA compared to conventional mixture. This clear indication is supported by Serin S et al. [6], which observed that steel fiber strengthens the interconnecting bonds between the bitumen molecules, enhancing cohesion and adhesion properties of SMA when being exposed to moisture. It is also noted that the SMA samples with the steel fiber addition did not split in two at the end of the test, due to the strength contributed by the steel fibers bridging the crack. Comparison of results of different steel fibre proportions were carried out to arrive at the best percentage of steel fiber to be utilized in SMA. When all the results obtained were considered together, it can be interpreted that SMA mixture with steel fiber of 0.3% by weight of mixture is the best proportion to be adopted in enhancing the performance of SMA, among the other steel fiber proportions being investigated as it showed the most positive influence on the performance of SMA regarding the stability, abrasion loss and moisture susceptibility.

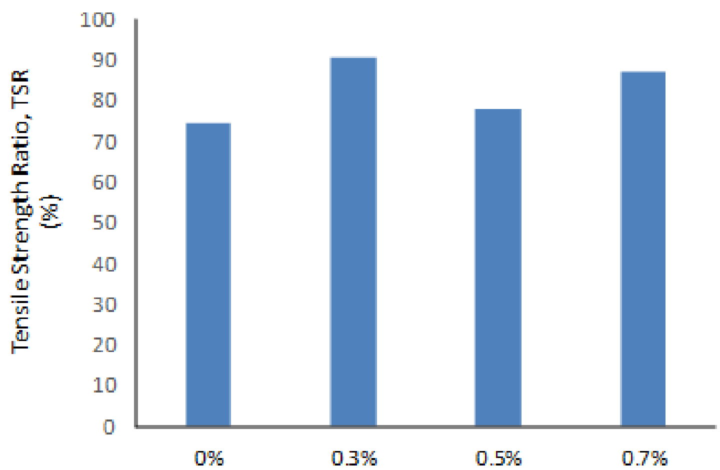


Fig. 9 - Tensile Strength Ratio (TSR) with different steel fiber content

3.4 Historical Data Design

A regression model for the responses were obtained consist of 15 sets of experiments that were used as design points for modelling. The range of the experimental data were used to set low and high values of factors and responses. The experimental matrix is tabulated in Table 3. Regression analysis was performed by the historical data design to fit the response function. The model was improved by manual reduction which involved elimination of larger insignificant terms.

Table 3 - Experimental matrix for historical data design

Std.	Run	Factor 1 A:Steel fiber %	Factor 2 B:ITS (dry) kPa	Factor 3 C:ITS (wet) kPa	Response 1 Tensile Strength Ratio %
7	1	0	432	399	74.29
14	2	0.35	360.5	399	90.58
6	3	0.7	289	399	86.98
15	4	0.35	360.5	306.5	90.58
9	5	0	360.5	306.5	74.29
10	6	0.7	360.5	306.5	86.98
3	7	0	432	214	74.29
8	8	0.7	432	399	86.98
5	9	0	289	399	74.29
13	10	0.35	360.5	214	77.74
11	11	0.35	289	306.5	90.58
4	12	0.7	432	214	86.98
12	13	0.35	432	306.5	90.58
2	14	0.7	289	214	86.98
1	15	0	289	214	74.29

The detailed of proposed model for responses were presented in Table 4. As the P-value less than 0.05, ANOVA were constructed based on Quadratic model. The F-values for the model is 4.8722 which significant model. This implies that the models represent data within the 95% Confidence Interval (CI). The 95% CI ($P < 0.05$) could be used to determine the significance model.

Table 4 - Model proposed for RSM

Response	Description	Sum of Squares	Degree of Freedom	Mean Square	F-Value	Prob > F	Model
TSR	Regression	642.6096	9	71.4011	4.8722	0.048	Quadratic
	Residual Error	73.2736	5	14.6547			
	R^2			0.8976			
	Adjusted R^2			0.7134			
	Predicted R^2			0.1451			
	Standard Deviation			3.83			
	Mean			83.09			
	Adequate Precision			5.8507			

The adequacy of the regression model was also ascertained between the experimental data and the model response with the diagnostic plot shown in Fig. 10. The adjusted R^2 is 0.7134 and predicted R^2 is 0.1451 were obtained from the regression line. The predicted and actual values of experimental response of statistical R^2 values indicated decent correlation. It can be observed that the Quadratic regression model fits realistically, thereby adequately expressing the experimental range studied. The normal plot of residuals depicts the graphical analysis of the model as exhibited by Fig. 11.

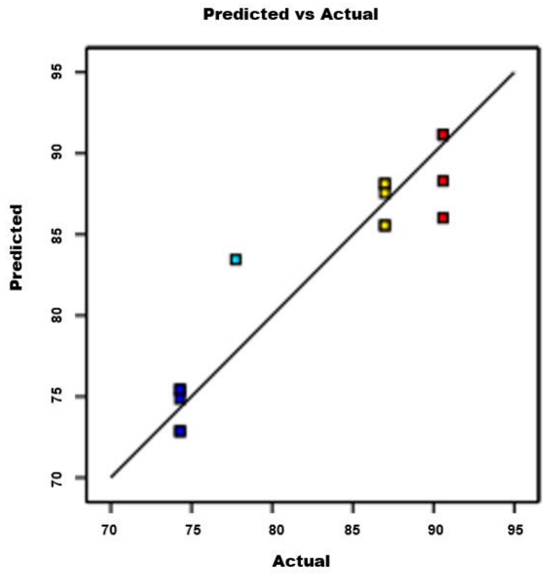


Fig. 10 - TSR cross plot between the predicted and experimental values

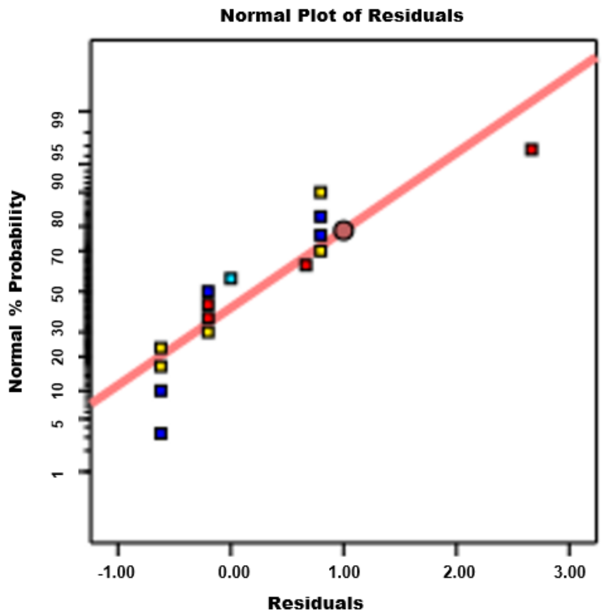


Fig. 11 - TSR Normal plot of residuals for the model

ANOVA was tabulated in Table 5 and used to analyse the adequacy of the model. The p-value of less than 0.005 indicate that the terms are significant. The model terms and their interactions were assigned negative and positive signs to indicate the antagonistic or synergistic effects of the variables on the performance of asphalt mixes. The models for the TSR of asphalt mixtures comprising all the terms are shown in Equation (1):

$$Y_{tsr} = 88.3+6.345A+1.284C-7.092A^2+2.85B^2-3.57C^2 \qquad (1)$$

Where A, B and C are parameters, refer to steel fibre, ITS (dry) and ITS (wet), respectively.

The effect of interaction between independent factors with responses variables were illustrated in three-dimensional (3D) response surface plots. Fig. 12 depicted the response surface model for Tensile Strength Ratio (TSR). A linear relationship can be observed between independent variables and response. Change in steel fibre content, ITS (dry) and ITS (wet), can greatly influence the TSR which evidently showed by the red region and blue region. Red region which represent the maximum value of TSR produced due to increase in independent variables content while blue region which represent minimum value of TSR were due to decrease in steel fibre content, ITS (dry) and ITS (wet).

Table 5 - ANOVA analysis for response model

Response	Factor	Sum of Squares	Degree of Freedom	Mean Square	F-value	Prob > F
TSR	A-Steel fibre	402.5903	1	402.5903	27.47171	0.0034
	B-ITS (dry)	0	1	0	0	1
	C-ITS (wet)	16.4866	1	16.4866	1.125	0.3373
	AB	0	1	0	0	1
	AC	0	1	0	0	1
	BC	0	1	0	0	1
	A^2	129.3216	1	129.3216	8.8246	0.0311
	B^2	20.9353	1	20.9353	1.4286	0.2856
	C^2	32.7114	1	32.7114	2.2321	0.1954

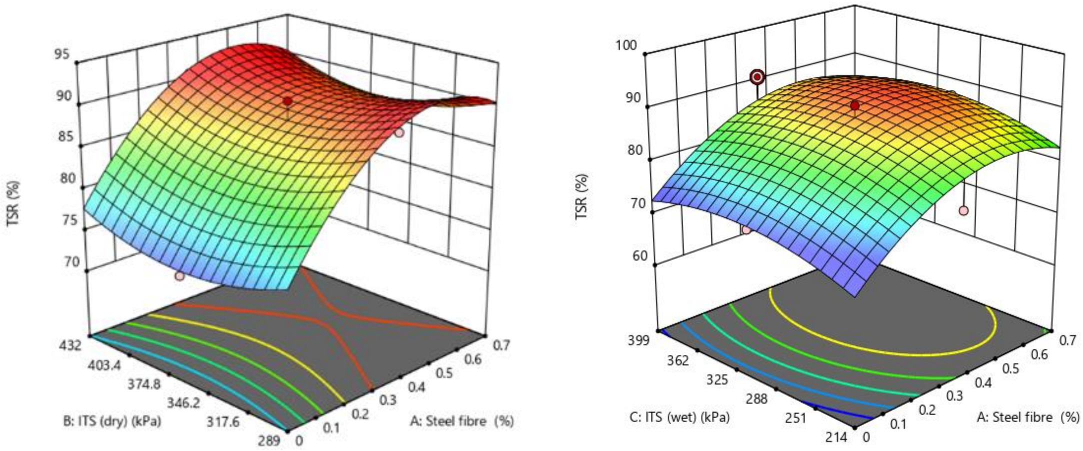


Fig. 12 - Response surface model for tensile strength ratio

The model optimization process was conducted to determine the factor conditions that give maximum tensile strength ratio. All the factors and responses with their particular lower and upper limits were re-specified for the optimum state and best resistance to pavement failure based on the PWD specifications. Fig. 13 illustrates the predicted optimum conditions and the response studied in this paper. The corresponding predicted ultimate axial strain, tensile strength ratio and stability were found to be 89%.

Fig. 13 - Optimum conditions and responses

4. Conclusion

Based on the results obtained from the experimental works conducted and the detailed analysis, the following conclusions are drawn:

1. The remarkable characteristics and properties of steel fiber have contributed to a significant improvement in the performance of SMA mixture regarding the resistance towards deterioration in asphalt pavements. It is found that SMA modified steel fiber enhances stability and abrasion resistance.
2. The Indirect Tensile Strength (ITS) value of SMA incorporating steel fiber indicated that the difference between wet and dry condition samples were insignificance compared to the conventional SMA without modification. Generally, appropriate content of steel fiber in SMA has high capability to provide SMA with adequate resistance towards moisture-induced damage, eventually increasing the life span of pavement.
3. It is revealed through the study that the incorporation of 0.3% steel fiber by weight of mixture can be categorized as the most optimum amount of steel fiber content to be utilized as a modification to SMA.
4. The overall findings in this study suggest that steel fiber has a good potential as SMA modifier. Long-term investigation including the use of scanning electron microscope images, rutting, fatigue and other mechanical performance, however, have been put forward for future study to obtain better understanding of this material in asphalt mixture.
5. The developed models between the independent variables and responses showed good degrees of correlation. The study revealed that the Response Surface Methodology (RSM) is an effective statistical method for providing appropriate empirical model for relating parameters and predicting the optimum performance of asphaltic mixture to reduce flexible pavement failure.

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