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Reinforcement of Asphalt Concrete Mixture using Recycle Polyethylene Terephthalate Fibre

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Abstract

Objectives: To determine the reinforcing effect of a cheap Recycle Polyethylene Terephthalate (PET) fibre on asphalt concrete strength. The aim of this study was achieved by performing Resilient Modulus (MR) test in the laboratory on both unreinforced (i.e. neat asphalt mixture) and recycle PET fibre reinforced asphalt concrete mixtures. **Methods:** The percentage additions of recycle PET fibres are 0.3%, 0.5%, 0.7% and 1% of the total weight of the mixture. The result was analyzed by means of Response Surface Methodology (RSM) using Design Expert 7.0 software and validated using analysis of variance (ANOVA). **Findings:** The results indicated that recycle PET fibres have significantly increased the mixtures' resilient modulus in lower temperature hence improved fatigue resistance, and moderately increased mixtures, resilient modulus at higher temperature hence improved rutting resistance. **Novelty/Improvement:** This research has introduced a sustainable means of producing Recycle fibres for the reinforcement of asphalt concrete mixtures. Recycle PET fibre have proved to be effective in strength improvement at 0.7% of total weight of asphalt concrete mixture.

Keywords: Fatigue, Fibre, Polyethylene Terephthalate, Resilient Modulus, Rutting, Temperature

1. Introduction

Asphalt concrete mixture is a combination of aggregates, bitumen, filler and additives for strength improvement. Asphalt concrete pavements are exposed to many factors that tend to undermine its strength. Thus moisture, repetitive traffic loading, ageing and sub-grade condition could lead to early failure if not carefully considered during design and construction stages. Although, the aforementioned factors plays important role in asphalt concrete failure but mixture's quality is also essential. In this regard, performance of asphalt concrete mixtures has been improved through its reinforcement with different types of fibre such as polypropylene[1,2], polyolefin-aramid[3], polyvinyl alcohol[4], polyester[5], polypropylene-impregnated multifilament glass fibres[6] and polyacrylonitrile[7].

In[8] investigated the mechanisms of different fibre types for stabilizing and reinforcing asphalt binder, their research involved the study of binders modified with Polyester, Polyacrylonitrile, Lignin and Asbestos fibres. It was observed that fibres significantly improved asphalt's dynamic shear modulus, rutting resistance and resistance to flow due to their spatial networking, absorption and adhesion. Additionally, in their effort to reduce the high Optimum Bitumen Content (OBC) of Steel Slag Asphalt

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Concrete (SSAC), Polypropylene (PP) fibre was used by[1] which successfully reduced the OBC by 19% compared to the neat mixture. It also increased tensile strength and resilient modulus of the mixture. Furthermore[3] ,presented a research on reinforcement of asphalt concrete mixture using synthetic fibre and compared its performance with that of styrene-butadiene-styrene (SBS) modified asphalt and neat asphalt concrete. Their result suggested that cyclic fatigue performance of fibre reinforced and SBS modified mixtures exhibited better than neat asphalt mixture. Although SBS modified mixture performed better than fibre reinforced mixture under smaller fatigue strains but fibre reinforced mixture performed better at higher strains.

Moreover,[9] investigated the effects of Recycled Synthetic Fibre (FC), Cellulose Fibre (FA) and cellulose + glass fibre (FB) in reinforcement of asphalt concrete mixture. Using 3%, 6% and 9% fibre (by weight of bitumen) their findings stated that cellulose fibres have shown convincing mechanical performances and high absorption of bitumen. Finally they concluded that there is a need for careful control of mixing and compaction temperatures and procedures to achieve a tough fibre reinforced asphalt concrete mixture. In[10] reported a good bonding effect and stabilization of cellulose fibres than mineral and carbon fibres in reinforcement of asphalt binder, they further stated that these fibres can improve rut and flow resistance of asphalt mortar. In[5] Recommended the use of 0.45% brucite fibre for effective enhancement of high temperature stability, low temperature crack resistance and improve moisture susceptibility of asphalt concrete mixture.

The current research trend on fibre reinforced asphalt concrete focuses on standard synthetic fibres that are too expensive[11].Therefore there is need of affordable fibres for strength improvement of asphalt concrete mixture.

On the other hand, global solid waste production is increasing in alarming rate due to growth of economic activities. More than 80% of generated solid waste in low and middle income countries are placed in landfills[12], out of which 25% is plastics[13]. In[14] it was reported that Polyethylene Terephthalate (PET) bottles made 60% of plastic waste generated. Polyethylene Terephthalate (PET) is a ubiquitous thermoplastic polymer used for daily household objects and soft drink containers. PET has a melting point of 260°C, high mechanical strength and fatigue resistance at 150 - 175°C[15]. Due to the promising mechanical characteristics of PET, researchers have been using it in strength improvement of asphalt concrete mixture.

Introduction of PET in asphalt mixtures would improve pavements performance and reduce global environmental pollution sustainably[16], thusperform double functions[17].

Although, modification and reinforcement of bituminous mixes with virgin polymers proved to be effective, the use of waste plastics show a similar effectiveness[18]. Recycle PET is used for modification of asphalt concrete in many ways: to modify bitumen[19], to coat aggregates[20] against moisture and also as partial replacement of aggregates[21].

Consequently, modification of bitumen with PET needs mechanical blending machineries[22], or compatibility agents that would disperse the PET homogenously in the bitumen binder[23]. The use of blending equipment and compatibility agents tend to incur more cost in bitumen modification and when successfully blended, the storage stability of PET modified bitumen is poor[24]. Also coating of aggregates with PET demands higher energy which means higher cost, and risk the strength of the aggregates as it is subjected to higher temperature normally above 250°C. However, in this study PET bottles are used to produce PET recycle fibers which are incorporated into asphalt concrete mixtures for strength improvement. The objective of this study is to determine the effect of recycle PET fibres and temperature on the performance of asphalt concrete mixture using resilient modulus test.

2. Methodologies

2.1 Materials

The conventional materials used in asphalt concrete are aggregates as the major constituent[25], bitumen binder and additives for strength improvement[18]. In this investigation, aggregates selection was based on quality, gradation was performed according to super pave mix design with maximum nominal aggregates size (NMAS of 12.5mm. The optimum bitumen content (OBC) of 6% was determined using AASHTO T312[26] procedure, while the samples were produced at 165°C and compacted using gyratory compactor at 155°C. The properties of materials used in this study are presented in Tables 1, 2 and 3 for aggregates, bitumen and asphalt concrete mixture respectively.

Table 1. Mechanical Properties of Aggregates used in this study

Property	Specification	Value (%)	Requirement (%)
Flakiness Index	BS 812 Part 105.1	15	<20
Elongation Index	BS 812 Part 105.2	17	20<
Aggregate Impact Value	812BS	21	30<
Aggregates Crushing Value	BS 812 Part 2	21	30<

Table 2. Properties of Asphalt binder used in this study

Test	Specification	Value
Penetration @ 25⁰C	ASTM D5-97	83
Softening Point	ASTM D3461	43

Table 3. Volumetric Properties of Asphalt Concrete Mixture used in this study

Property	Value	Requirement
Air Void	4	4
VMA	16	13 minimum
VFA	75	65 – 75
OBC	6	4 – 11

Recycle PET fibre was produced using shredder, PET bottles were collected, washed and cut to sheets (Figure 1) then shredded using paper shredding machine to the size of 0.4 x 10mm (Figure 2). This size is within the fibre sizes used by[2,4,27,28] in modification of asphalt concrete mixture.

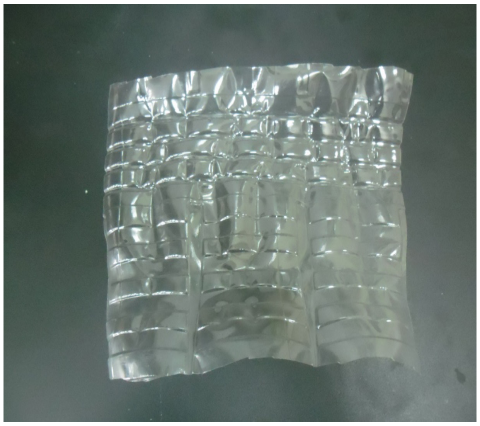

Figure 1. Recycle PET sheet.

Figure 2. Recycle PET fibres.

2.2 Method of Blending Recycle PET Fibre in Asphalt Concrete Mixture

The recycle PET fibres were added to the asphalt concrete mixture at 0.3%, 0.5%, 0.7% and 1% to the total weight of mixture. Recycle PET fibres were blended in the mixture by means of dry Process as suggested by[2,6,20]. Aggregates were heated at 165°C and mixed thoroughly with recycle PET fibres, and then finally mixed with bitumen.

2.3 Experimental Test

Experimental samples were prepared as explained in sections 2.1 and 2.2 above for reinforced and unreinforced (neat asphalt concrete) mixtures. The unreinforced samples contain 0% recycle PET fibre which served as control, while reinforced samples contain 0.3%, 0.5%, 0.7% and 1% so as to determine optimum fibre content base on performance. The prepared samples were subjected to resilient modulus (MR) test.

Resilient Modulus (MR) is a measure of pavement response of dynamic stresses and corresponding strains, it is an important parameter used among researchers in determining the mechanical properties of asphalt mixtures which can be used in the mechanistic design of pavement structures[29]. The test is non destructive, the specimens preparation and testing was base on ASTM D4123[30] using Universal Testing Machine (IPC UTM-5P). Base on mix design, three numbers of specimens for each type of mixtures were prepared and compacted. Prior to the testing, samples and testing equipment were conditioned at the ambient testing temperatures of 25°C (low temperature) and 40°C (high temperature) in the environmental chamber for two hours.

The specimen was then mounted on the universal testing machine chamber containing linear variable differential transformer(LVDTs) to sense the responses, and then set with a have sine wave pattern using five count of conditioning pulses followed by five loading pulses and the result is recorded. In addition, the load was set up for a period of 100 ms pulse width and 1000 ms for pulse repetition period which represent high traffic volume[31].

2.4 Method of Analysis

Response surface methodology (RSM) was used in the analysis of data obtained in this research, RSM has been used by[32–34] for the analysis of their various research outcomes on bituminous mixtures. RSM is a statistical tool used for predicting the relationship between factors and responses and also in the analysis of problems[35,36].

Using Design Expert 7.0 software, two factors (PET fibre percentage and temperature) and one response (resilient modulus) were analyzed at 30 runs using historic data as shown in Table 4.

To estimate the response variable, a Montgomery[36] quadratic polynomial regression model was used for four independent variables as shown in Equation 1.

$$Y = b_0 + \sum_{i=1}^{n} b_i x_i + \sum_{i=1}^{n} b_j x_i^2 + \sum_{i=1}^{n} \sum_{j=1}^{n} b_j x_i x_j + \varepsilon \quad (1)$$

Y is resilient modulus (i.e. response variable), n is the number of factors, ε is random error, b_0, b_i, b_{ii} and b_{ij} are constant coefficients of intercept, linear, quadratic and interaction terms (independent variables) respectively.

3. Results and Discussion

3.1 Model Fitting

Response surface methodology was used to estimate the interactions between factors and response which is reported in table 4, the quadratic polynomial equation for resilient modulus (MR) was produced by the software after regression analysis and is presented as Equation 2.

$$MR = 5410.69 + 2555.52x_1 - 123.66x_2 - 63.3x_1x_2 \quad (2)$$

Where MR is resilient modulus, x_1 and x_2 are PET fibre percentage and temperature respectively.

The model was checked by means of analysis of variance (ANOVA) and the result is summarized in Table 5.

Table 4. Experimental layout and responses for reinforced and un-reinforced asphalt concrete mixtures

Run	Factors		Response	Run	Factors		Response
	PET Fibre %	Temperature °C	Resilient Modulus (MPa)		PET Fibre %	Temperature °C	Resilient Modulus (MPa)
1	0.0	25	3144	16	0.5	40	549
2	0.0	25	2298	17	0.5	40	489
3	0.0	25	1023	18	0.5	40	427
4	0.0	40	455	19	0.7	25	3389
5	0.0	40	500	20	0.7	25	4447
6	0.0	40	473	21	0.7	25	3303
7	0.3	25	2541	22	0.7	40	583
8	0.3	25	2851	23	0.7	40	480
9	0.3	25	2494	24	0.7	40	582
10	0.3	40	450	25	1.0	25	2965
11	0.3	40	359	26	1.0	25	2865
12	0.3	40	441	27	1.0	25	2720
13	0.5	25	2738	28	1.0	40	448
14	0.5	25	2741	29	1.0	40	439
15	0.5	25	2566	30	1.0	40	465

Table 5. Analysis of variance for Resilient Modulus

Parameter	DF	SS	MS	F-Values	P-Values	Model Performance
Regression	3.00	42350000	14120000	66.69	<0.0001	Significant
Residual Error	26.00	550400	204000	-	-	
Lack of fit	6.00	2266000	377700	2.33	0.0717	Insignificant
Pure Error	20.00	3238000	161900	-	-	
Total	29	47860000	-	-	-	
R^2	88.5					

The suitability of this model is emphasized by a very low P-value (p<0.0001) which indicate the significant performance of the model[32]. Lack of fit is used to check the variation of data around the model, in this research the insignificant value of 0.07 lack of fit was realized which implies that the model is well fitted for the analysis[37].

Another factor for determining model fitting is regression coefficient of determination (R^2), the value of R^2 in this study is 88.5 which is very strong indicator of acceptable statistical analysis[38]. Figure 3 is a normal probability plot for MR, an approximate normal data distribution can be seen around the graph line, when data is poorly distributed the points will depart away from the graph line meaning departure of data from normality[39].

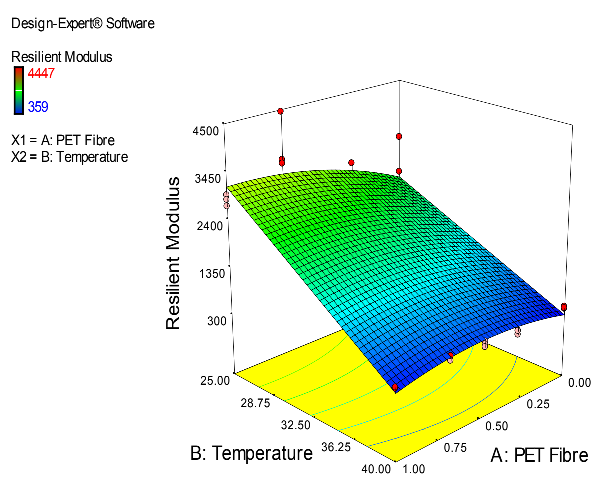

Figure 3. Surface Plot for MR vs Fibre & Temperature.

3.2 Effects of PET Fibres and Temperature on Resilient Modulus

Recycle PET fibre has positive effect on asphalt concrete mixture as indicated by resilient modulus test result in Table 4 and Figure 4. Resilient modulus at 25^{O}C is a measure of mixture's fatigue resistance and indicator of rutting resistance at 40^{O}C[40]. Temperature and PET fibres have direct impact on the resilient modulus of asphalt concrete mixture. Figure 3 is surface plot for resilient modulus versus recycle PET fibre and temperature, it is clear that resilient modulus increases with the increase of PET fibres and decrease with increase of temperature.

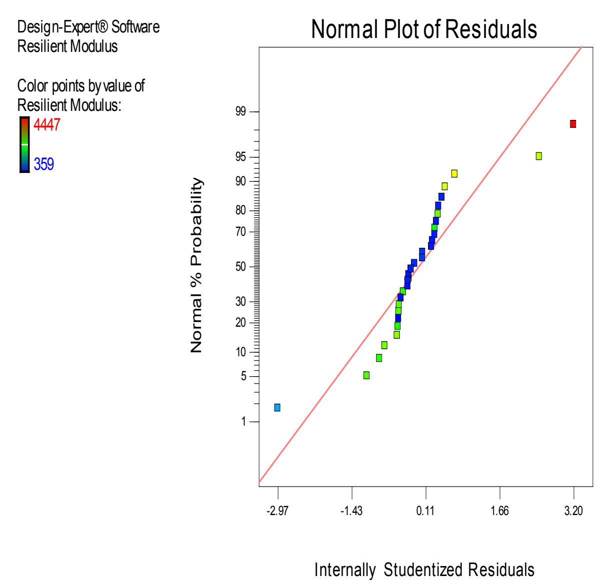

Figure 4. Normal Probability Plot- MR.

This is further explained by one factor plot for recycle PET fibre/resilient modulus and temperature/resilient modulus shown in Figures 5 and 6 respectively. In figure 5, as the percentage of PET fibre increases so resilient modulus until optimum fibre content is reached at 0.7%, after which it dropped at 1% addition of recycle PET fibre. The improvement in mixtures' resilient modulus is due to tensile forces and lateral confinements provided by recycle PET fibres[41]. While the drop in resilient modulus at 1% shows a critical fibre fraction as the fibres start to interact with each other which resulted in lower resilient modulus[42].

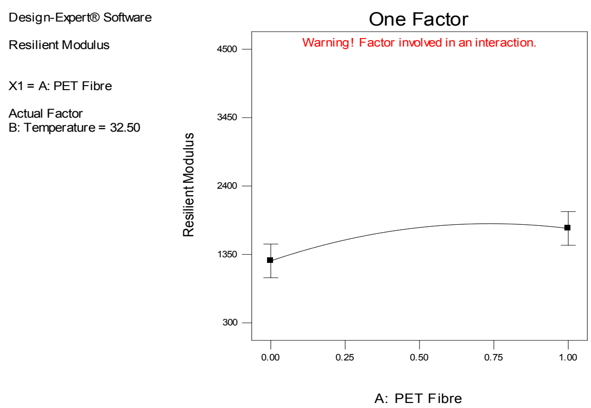

Figure 5. One factor plot for PET Fibre % and resilient modulus.

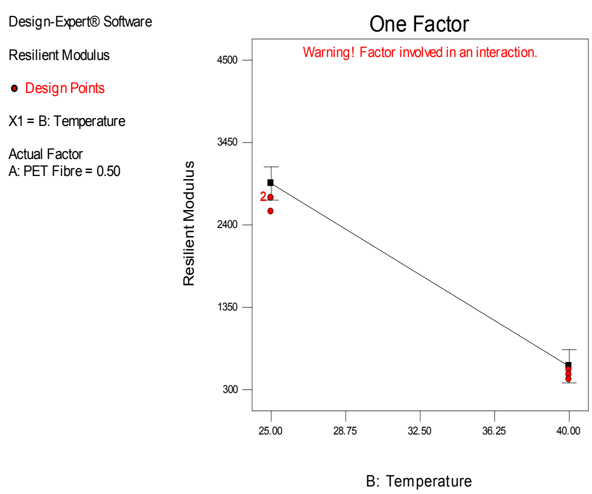

Figure 6. One factor plot for temperature and resilient modulus.

Similarly, Figure 6 presents one factor plot for the effect of temperature on mixture's resilient modulus. Resilient modulus decreases with the increase of temperature from lower to higher temperature[43] (i.e. 25^{O}C to 40^{O}C). The decrease in resilient modulus with an increase of temperature is as a result of high temperature sensitivity of asphalt binder due to its visco elastic characteristics. In comparison, at 40^{O}Cthe performance of recycle PET reinforced asphalt concrete mixture has improved by 15% than neat asphalt concrete mixture. This improvement is due the mechanical strength possessed by recycle PET fibres when subjected to temperatures below 175^{O}C[15].

Furthermore, as indicated in Figure 3 it is evident that resilient modulus of recycle PET fibre reinforced asphalt mixture at 25^{O}C and 40^{O}C have been significantly increased which is in line with the research findings of[1], hence recycle PET fibre have improved the fatigue and rutting resistance of the asphalt concrete mixture..

4. Conclusion

The purpose of this paper is to determine the effect of recycle PET fibre and temperature on the performance of asphalt concrete mixture. Using response surface methodology and analysis of variance (ANOVA), the data obtained was analyzed and the following conclusions are drawn: Recycle PET fibre have improved the fatigue and rutting resistance of asphalt concrete mixtures. The improvement of resilient modulus in PET reinforced asphalt concrete is more significant at lower temperatures than higher temperatures. The optimum fibre content is 0.7% of total weight base on performance.

5. Acknowledgement

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