Performance Prediction Models of Crumb Rubber-Modified Asphaltic Concrete

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Abstract
The tyre component of solid waste is a very promising candidate for recycling, and this investigation studied the use of waste tyre crumb as partial replacement for fillers in flexible pavement wearing course. The fillers were substituted with different percentages of crumb rubber (5, 10, 20, 30, 40 and 50%). The Marshall design test was used to examine the influence of the modifier (waste tyre crumb) on the Optimum Bitumen Content (OBC), stability, flow and void properties of the asphalt concrete. The results obtained were then used to develop models to predict the performance of crumb rubber modified asphaltic concrete.Results obtained showed that partial replacement of crumb rubber up to 20% for mineral filler provided satisfactory results in terms of Stability, Flow, Void Minerals in Aggregate (VMA) and Void Filled with Asphalt (VFA) for dense graded HMA wearing course.
Keywords: Asphaltic Concrete, Crumb rubber (CR), Marshall Design, Performance Prediction Model, and Optimum Bitumen Content (OBC).

1. Introduction

One of the most important threats to the environment is the accumulation of waste materials such as rubber, glass, metal, plastic, etc. As the population increases, the amount of waste is rapidly growing and the disposal of waste is also increasing proportionally. There are three major ways to deal with waste materials: burying, incineration, and recycling. Recycling and reusing waste materials can be effective to reducing consumption of natural resources and also in mitigating environmental pollution (Batayneh et al., 2007; Marzouk et al., 2007; Canestrari et al., 2009).

The global problem with landfill disposal of automobile tyres can only be solved by the feasible option left, and that is recycling and utilization of the recycled products. It is thought that the application of recycled automobile tyres will not only solve the environmental menace of these industrial solid wastes but also act as very promising modifiers for the improvement of asphalt pavement material (M. Sienkiewicz, et. al. 2012).

Tyre recycling (or rubber recycling) is the process of recycling vehicles' tyres that are no longer suitable for use on vehicles due to wear or irreparable damage (such as punctures). These tyres are among the largest and most problematic sources of waste, due to the large volume produced, their short time durability, and the fact they contain a number of components that are ecologically problematic. It is estimated that 259 million tyres are discarded annually. The same characteristics that make waste tyres problematic, their cheap availability, bulk, and resilience, also make them attractive targets for recycling (Foraminifera Market Research, 2015).

The volume of solid waste generated annually in Nigeria is growing steadily, while at the same time the available capacity of disposal sites is shrinking. There are presently several methods of solid waste disposal in use, but many have serious disadvantages. The oldest method of disposal is the open dump. Substantial quantities of used tyres are being discarded annually throughout the world and this is likely to increase in line with the growth in road traffic. Large quantity rubbers are widely used in various industry applications, such as tyres, seals and gaskets in automotive, aerospace and many more but automobile industry is the biggest consumer of rubber (Anjali B. et. al. 2017). The utilization of crumb rubber as recycled materials in pavement engineering creates landfill avoidance, reduces environmental concerns attributed to tyre dumpsites and encourages its usage as raw materials or modifiers (Zaumanis Martins, Mallick Rajib B. and Frank Robert, 2014). Recycling these wastes can save energy and decrease environmental wastes. However, in many parts of the world, recycling and use of tyre in engineering works is still at its infancy.

Due to the abundance of discarded tyres, many states have pursued the reuse of rubber tyres in pavements. Adding rubber to asphalt has similar benefits as adding additives to concrete. The additives materials helped the engineers to improve the asphalt for some special required specifications. Rubber asphalt is produced either by wet process (rubber is melted in the liquid asphalt binder before mixing), or by dry process: rubber replaced by a portion of fine aggregate during mixing (Huang et al. 2007).

According to laboratory binder tests, it is clear that rubber crumb content played a main role in influencing significantly, the performance and rheological properties of rubberized bitumen binders (Mashaan and Karim, 2011; 2013).

Navarro et al. (2002) studied the rheological characteristics of ground tyre rubber-modified asphalt. The experiment was performed in a controlled-stress Haake RS150 rheometer. The study aimed at comparing the viscoelastic behaviour of five ground tyres rubber modified with unmodified asphalt and polymer-modified (SBS) asphalt. The study displayed that rubber-modified asphalt improved viscoelastic characteristics and therefore has higher viscosity than unmodified binders. Thus, the asphalt rubber is expected to better enhance resistance to permanent deformation or rutting and low temperature cracking. The study also found that the viscoelastic properties of rubber-modified asphalt with 9% weight are very similar to SBS-modified bitumen having 3% weight SBS at −10°C and 7% weight at 75°C.

Zaman et al. (2005) found that the viscosity of asphalt cement increases with the addition of rubber, and rubber-modified asphalt-cement samples show a more uniform and higher resistance against loading as the amount of rubber increased. The degrees of shear-thickening and shear-thinning behaviour decreased by increasing the amounts of rubber in asphalt cement. The liner dynamic viscosity was increased by increasing the amount of rubber in asphalt cement. Piggott et al. (1977) mentioned that the vulcanized rubber had a large effect on the viscosity of the asphalt cement. The viscosity, measured at 95°C, increased by a factor of more than 20 when 30% vulcanized rubber was added to the mixture. In contrast, the de-vulcanized rubber had only a very small effect. The viscosity test also showed that there is no danger of gel formation when rubber is mixed with hot asphalt cement.

Mahrez (1999) investigated the properties of asphalt rubber binder prepared by physical blending of asphalt 80/100 penetration grade with different crumb rubber content and various aging phases. The results of penetration values decreased over the aging as well as before aging by increasing the rubber content in the mix. Also, the modified binders showed lower penetration values than unmodified binders. Another study (Kumar et. al. 2009) on penetration change was conducted using asphalt 80/100 and 70/100 penetration grade mixes with different crumb rubber percentage. The results showed a significant decrease in the penetration values of modified binder due to high crumb rubber content in the binders.

Mashaan and Karim (2013) reported that the softening point value increases as crumb tuber content increases in the mix. The increase of rubber content in the mix could be correlated to the increase in the asphaltenes/resins ratio which probably enhanced the stiffening properties, making the modified binder less susceptible to temperature changes.

According to Liu et al. (2009), the main factor in the increase in softening point can be attributed to crumb rubber content, regardless of type and size. The increase in softening point led to a stiff binder that has the ability to enhance its recovery after elastic deformation.

The results of Marshall Test by Samsuri (1997) indicated that incorporation of rubber increases the Marshall stability and quotient. The increase varied with the form of rubber used and the method of incorporating the rubber into bitumen. The Marshall stability for mixes containing rubber powders was increased more than twofold and the Marshall quotient increased by nearly threefold compared to the normal unmodified bituminous mix. Mixes produced using bitumen pre-blended with fine rubber powders showed the greatest improvement than mixes produced by direct mixing of rubber with bitumen and aggregates. Thus, pre-blending of bitumen with rubber is a necessary step in order to produce an efficient rubberized bitumen binder probably due to adequate and efficient rubber dispersions in the bitumen phase.

2. Materials and Methods

2.1 Bituminous material

The asphalt binder used was obtained from Lagos State Public Works Commission (LSPWC). Laboratory tests were carried out to determine the properties of the bitumen, including penetration, viscosity, flash point and softening point.

2.2 Aggregates

The aggregates used for this study were from stockpiles with sizes (mm) of 0-0.75mm (fillers), 0-4 (fine sand), 0-5 (stone dust), 4-8 (crushed stone) and 8-16 (crushed stone). They were properly dried, cleaned from deleterious materials and sieved.

2.3 Crumb Rubber

The crumb rubber used was obtained from Lagos State Public Works Corporation (LSPWC) yard at Imota, Ikorodu.

Plate 1: Crumb Rubber (0-0.75mm sizes)

In order to meet the objectives of this study, the following tests were conducted, as outlined in Table 1. The parameters that were varied are: bitumen content (5, 5.5, 6, 6.5, 7, 7.5 and 8%) and Crumb Rubber (5, 10, 20, 30, 40 and 50%).

Table 1: Laboratory Tests Conducted

Material	Laboratory Test
1ST SET OF TESTS	
Bitumen Sample	• Specific Gravity • Penetration • Viscosity • Softening Point • Flash Point
2ND SET OF TESTS	
Control Sample of Asphaltic concrete without any additives	• Specific gravity • Bulk Density • Marshall Stability and Flow
3RD SET OF TESTS	
Modified Asphaltic concrete (5, 10, 20, 30, 40 and 50% Crumb Rubber as partial replacement for fillers).	• Specific gravity • Bulk Density • Marshall Stability and Flow

3. Results and Analyses

3.1 Preliminary Test Results for the Asphalt Binder Used

The preliminary test results are summarized in Table 2

Table 2: Preliminary Test Results of the Asphalt Binder Used

Properties	Values	Standard Specification (ASTM)		Remarks
		Min.	Max.	
Specific Gravity at 25 °C	1.01	1.01	1.05	Satisfactory
Penetration at 25 °C, 100g, 5s	67.2	60	70	Bitumen 60/70
Viscosity (s)	22.5			
Softening Point (^{0}C)	49.5	45	52	Satisfactory
Flash point (^{0}C)	281.33	230	-	Satisfactory
Solubility in Trichloroethylene (%)	100	99	-	Satisfactory

3.2 Grading Analysis of Aggregates Used

This test reveals the blending ratios of the constituent aggregates that make up the asphalt concrete. This is expressed in Tables 3 and 4, as well as Fig 1.

Table 3: Aggregate Mix Proportion

Aggregate Size (mm)	Aggregate Type	% Proportion
8-16	Crushed Stone	20
4-8	Crushed Stone	15
0-5	Stone Dust	49
0-4	Washed Sand	8
0-0.75	Fillers	8

Table 4: Sieve Analysis of the Aggregate Mix

Sieve sizes (mm)	% Passing (Lower Limits)	% Passing (Aggregate Used)	% Passing (Upper Limits)
25	100	100	100
19	100	100	100
12.5	85	86.1	100
9.5	75	78.62	92
4.75	65	65.63	82
2.36	50	52.7	65
1.18	36	43.03	51
0.6	26	33.24	40
0.3	18	20.94	30
0.15	13	13.5	24
0.075	7	9.01	14

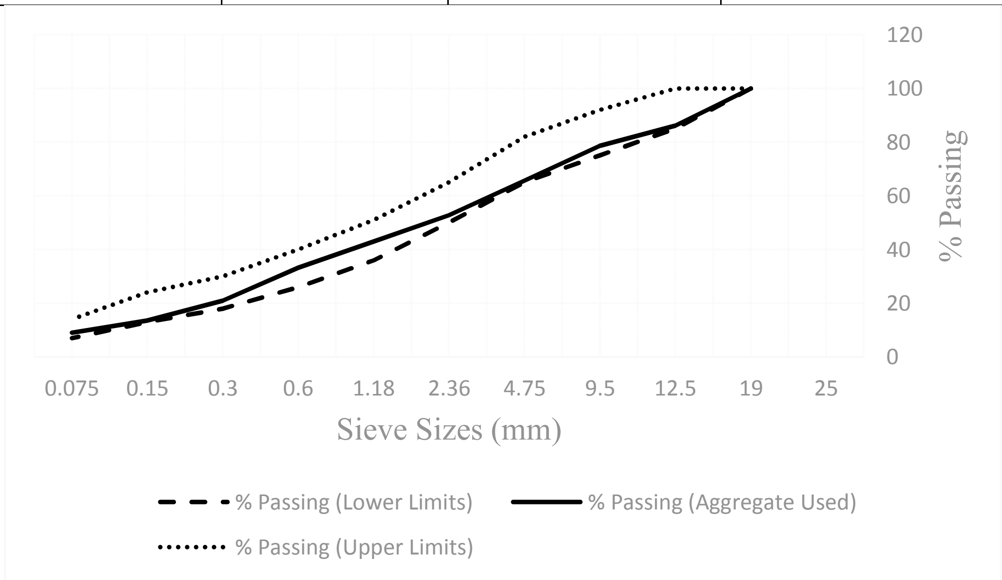


Figure 1: Sieve Analysis Curve for the Aggregate Mix

The curve shows that the mix proportion was satisfactory as the limits were not exceeded.

3.3 Marshall Test Results

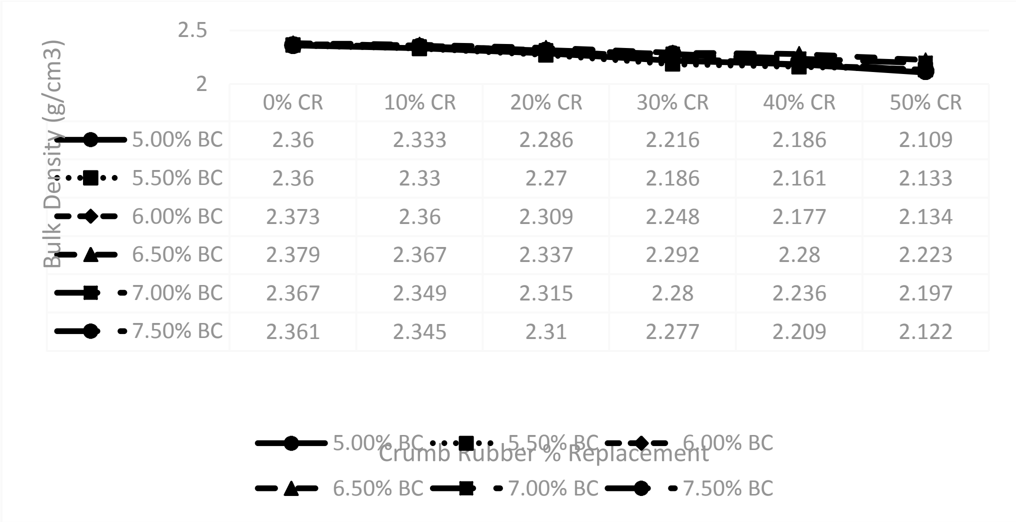
This test involves the determination of the resistance to deformation under wheel loading. The Marshall Test conducted on the asphalt concrete samples (control and modified) involve determination of the following:

i. Bulk Density and Theoretical Maximum Density
ii. Void Characteristics
iii. Marshall Stability and Flow Values

The results of Marshall Test are summarized in Table 5 and Figures 2 to 5.

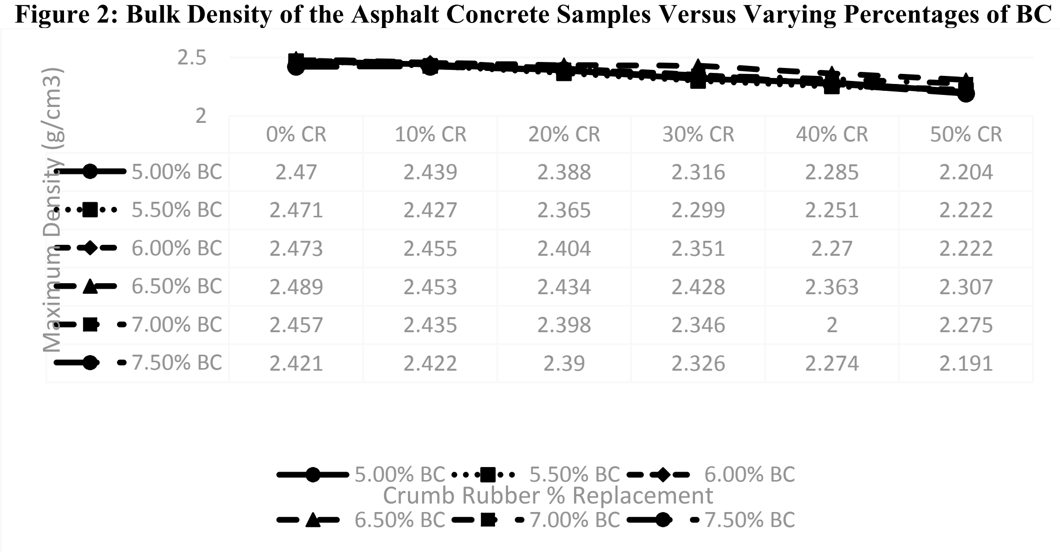
3.3.1 Bulk Density and Theoretical Maximum Density

The Figures 2 and 3 show the results and trend of the bulk density and maximum density of the control and modified asphalt concretes.



	0% CR	10% CR	20% CR	30% CR	40% CR	50% CR
5.00% BC	2.36	2.333	2.286	2.216	2.186	2.109
5.50% BC	2.36	2.33	2.27	2.186	2.161	2.133
6.00% BC	2.373	2.36	2.309	2.248	2.177	2.134
6.50% BC	2.379	2.367	2.337	2.292	2.28	2.223
7.00% BC	2.367	2.349	2.315	2.28	2.236	2.197
7.50% BC	2.361	2.345	2.31	2.277	2.209	2.122

Figure 2: Bulk Density of the Asphalt Concrete Samples Versus Varying Percentages of BC



	0% CR	10% CR	20% CR	30% CR	40% CR	50% CR
5.00% BC	2.47	2.439	2.388	2.316	2.285	2.204
5.50% BC	2.471	2.427	2.365	2.299	2.251	2.222
6.00% BC	2.473	2.455	2.404	2.351	2.27	2.222
6.50% BC	2.489	2.453	2.434	2.428	2.363	2.307
7.00% BC	2.457	2.435	2.398	2.346	2	2.275
7.50% BC	2.421	2.422	2.39	2.326	2.274	2.191

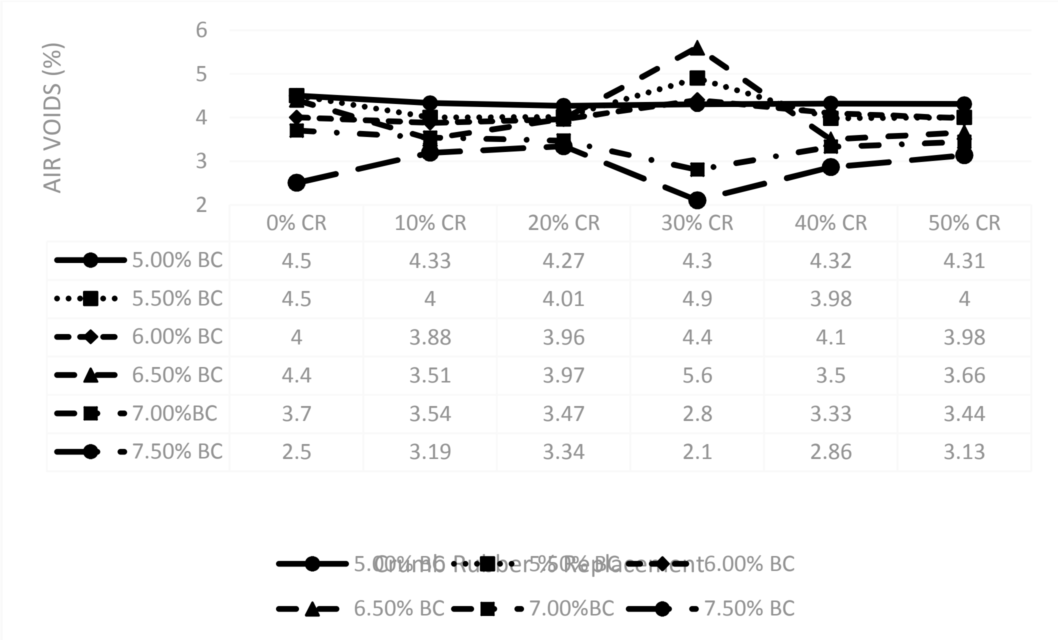
Figure 3: Maximum Density of the Asphalt Concrete Samples Versus Varying Percentages of BC

Discussion of Results

The results for both bulk and maximum densities show a steady decrease with increase in crumb rubber content at specific bitumen contents. This may be attributed to the low specific gravity of the crumb rubber.

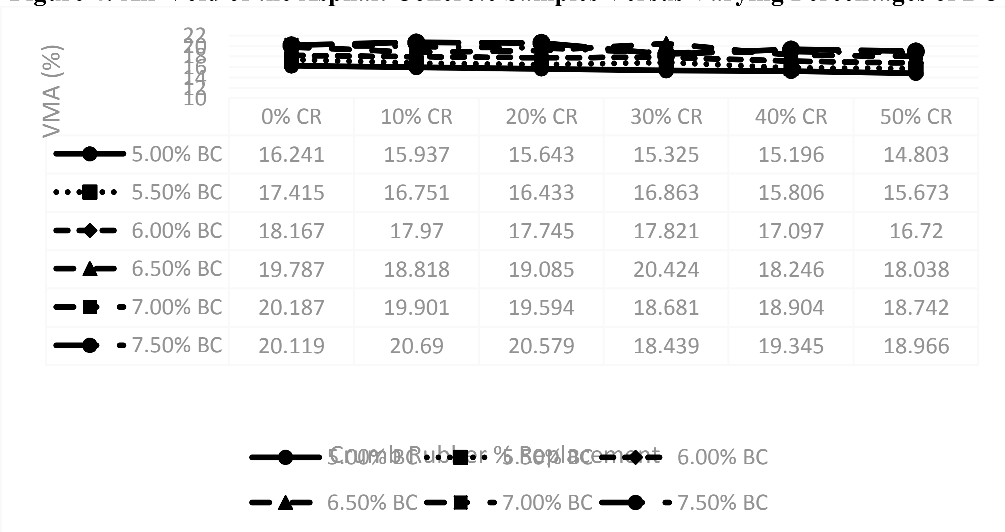
3.3.2 Void Characteristics

Figures 4, 5 and 6 show the trend and results of the void characteristics of the asphalt concretes (control and modified).



	0% CR	10% CR	20% CR	30% CR	40% CR	50% CR
5.00% BC	4.5	4.33	4.27	4.3	4.32	4.31
5.50% BC	4.5	4	4.01	4.9	3.98	4
6.00% BC	4	3.88	3.96	4.4	4.1	3.98
6.50% BC	4.4	3.51	3.97	5.6	3.5	3.66
7.00%BC	3.7	3.54	3.47	2.8	3.33	3.44
7.50% BC	2.5	3.19	3.34	2.1	2.86	3.13

Figure 4: Air Void of the Asphalt Concrete Samples Versus Varying Percentages of BC



	0% CR	10% CR	20% CR	30% CR	40% CR	50% CR
5.00% BC	16.241	15.937	15.643	15.325	15.196	14.803
5.50% BC	17.415	16.751	16.433	16.863	15.806	15.673
6.00% BC	18.167	17.97	17.745	17.821	17.097	16.72
6.50% BC	19.787	18.818	19.085	20.424	18.246	18.038
7.00% BC	20.187	19.901	19.594	18.681	18.904	18.742
7.50% BC	20.119	20.69	20.579	18.439	19.345	18.966

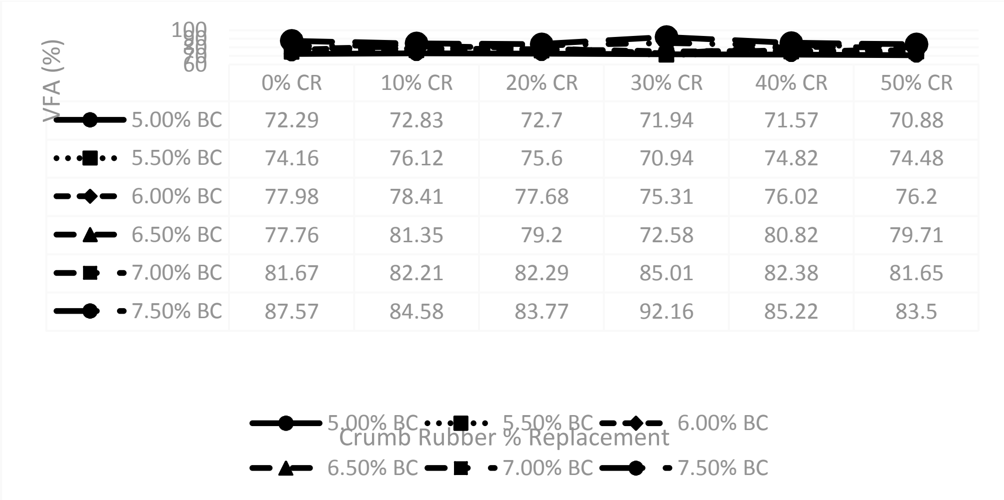
Figure 5: VMA of the Asphalt Concrete Samples Versus Varying Percentages of BC

Discussion of Results

At 5% bitumen content, air void decreased compared to the control sample, however, after 20% crumb rubber replacement, air void was observed to increase gradually with its peak at 40% CR replacement. At 5.5% to 6.5% bitumen content, air void decreased at 10% CR replacement, after which it increased at 20% and 30% CR replacement before reducing. At 7% bitumen content, air void decreased steadily up to 30% but after which increased but remained lower than that of the control samples. At 7.5% bitumen content, air void increased and remained higher than that of the control samples with exception at 30% CR with air void lesser than that of the control samples. This behavior can be attributed to the compaction properties for crumb rubber modified asphalt concrete. The samples which showed a lower air void compared to the control mix indicate better compaction properties.

The VMA results (Fig. 5) also showed a decrease compared to the control sample, with exception observed at 30% CR replacement for 6.5% bitumen content. This is because crumb rubber reduces the space available for asphalt film.

VFA results (Fig. 6) were observed to be higher than that of the control samples up to 20% CR replacement. However, at 7.5% bitumen content, VFA was lower than that of the control samples except for 30% CR replacement. A higher VFA indicates increased durability.



	0% CR	10% CR	20% CR	30% CR	40% CR	50% CR
5.00% BC	72.29	72.83	72.7	71.94	71.57	70.88
5.50% BC	74.16	76.12	75.6	70.94	74.82	74.48
6.00% BC	77.98	78.41	77.68	75.31	76.02	76.2
6.50% BC	77.76	81.35	79.2	72.58	80.82	79.71
7.00% BC	81.67	82.21	82.29	85.01	82.38	81.65
7.50% BC	87.57	84.58	83.77	92.16	85.22	83.5

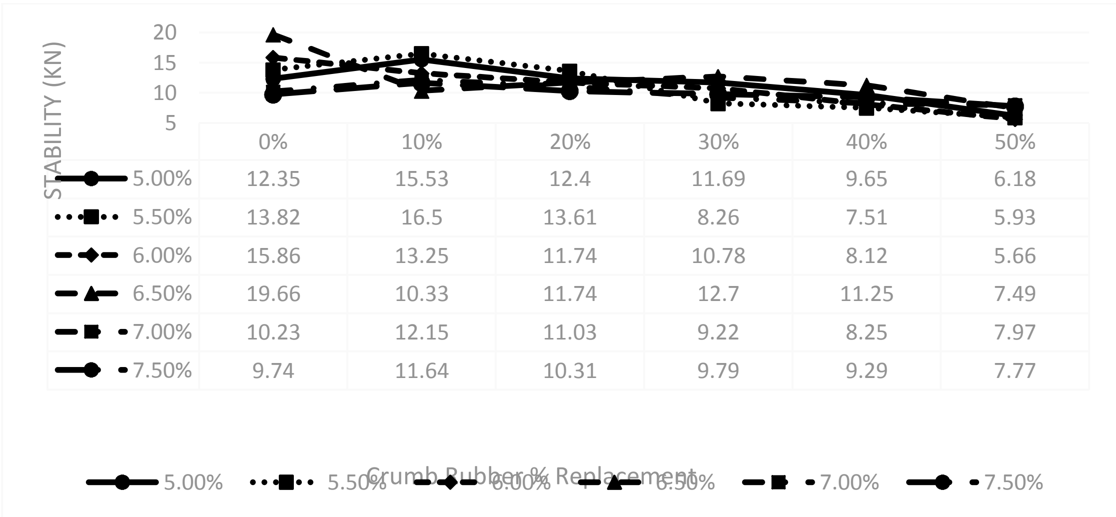
Figure 6: VFA of the Asphalt Concrete Samples Versus Varying Percentages of BC

3.3.3 Marshal Stability and Flow

Figures 7 and 8 express the trend and summarize the Marshal stability and flow results as obtained for the asphalt concretes.

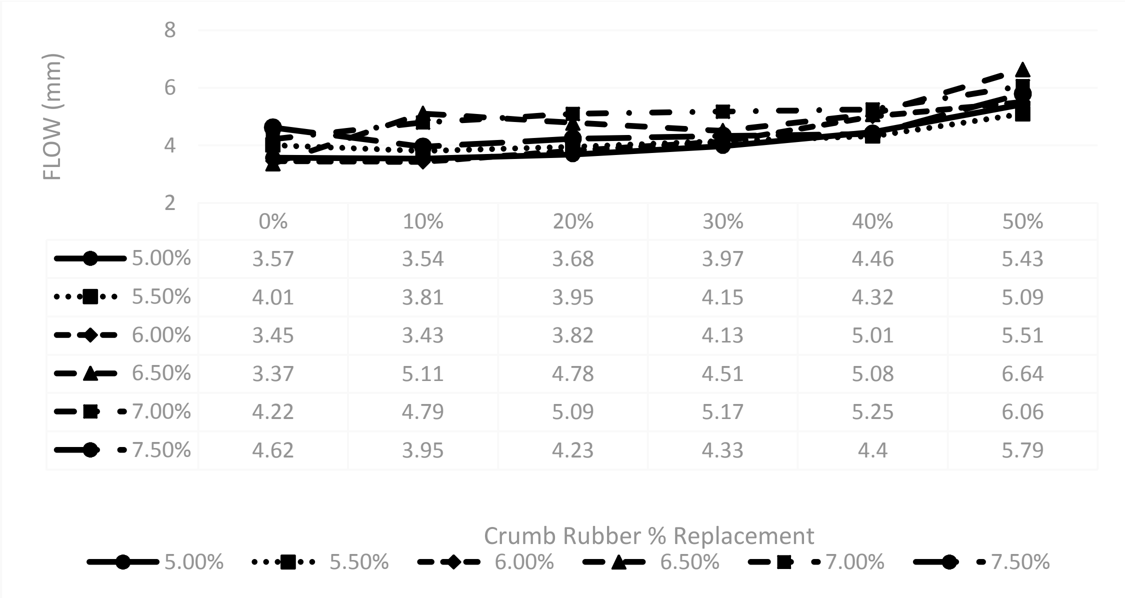
Discussion of Results

Marshal stability result shows optimum increase in stability at 10% and 20% crumb rubber replacement with peak values obtained at 10% crumb rubber replacement; after which a decrease in stability was observed with increase in crumb rubber when compared to the control samples. The increase in stability observed at 10% and 20% CR replacement can be attributed to the resistance crumb rubber offers to applied load but further injection of crumb rubber into the mixture led to a decrease in the value of stability because application of excessive crumb rubber decreases the coarse aggregate contact point within the mixture. As a result, the mixture becomes more flaccid and this contributes to the decrease in the value of stability. Low stability suggests low quality of aggregates. Most satisfactory result for flow was seen at 10% and 15% CR content for BC of 5, 5.5 and 6%. Increase in CR content and BC resulted in increase in flow values.



	0%	10%	20%	30%	40%	50%
5.00%	12.35	15.53	12.4	11.69	9.65	6.18
5.50%	13.82	16.5	13.61	8.26	7.51	5.93
6.00%	15.86	13.25	11.74	10.78	8.12	5.66
6.50%	19.66	10.33	11.74	12.7	11.25	7.49
7.00%	10.23	12.15	11.03	9.22	8.25	7.97
7.50%	9.74	11.64	10.31	9.79	9.29	7.77

Figure 7: Marshal Stability of the Asphalt Concrete Samples Versus Varying Percentages of BC



	0%	10%	20%	30%	40%	50%
5.00%	3.57	3.54	3.68	3.97	4.46	5.43
5.50%	4.01	3.81	3.95	4.15	4.32	5.09
6.00%	3.45	3.43	3.82	4.13	5.01	5.51
6.50%	3.37	5.11	4.78	4.51	5.08	6.64
7.00%	4.22	4.79	5.09	5.17	5.25	6.06
7.50%	4.62	3.95	4.23	4.33	4.4	5.79

Figure 8: Marshal Flow of the Asphalt Concrete Samples Versus Varying Percentages of BC

3.4 Optimum Asphalt Binder Content

The results, as obtained, were used to plot graphs that facilitated the selection of the optimum asphalt binder content. The graphs plotted were:

i. Air voids versus Asphalt Content
ii. Marshal Stability versus Asphalt Content
iii. Marshal Flow versus Asphalt Content
iv. VMA versus Asphalt Content
v. VFA versus Asphalt Content
vi. Density versus Asphalt Content

The optimum asphalt binder content results as derived from the plotted graphs are summarized in Table 5.

Table 5: Summary of Asphalt Concrete Properties

PROPERTIES	0% CRUMB RUBBER		
	RESULTS	AI SPECIFICATION	REMARKS
OBC (%)	6.00	5.0-8.0	
DENSITY	2.37		
VMA (%)	18.17	Minimum 13%	Satisfactory
VFA (%)	77.98	75.0-82.0	Satisfactory
STABILITY (KN)	15.86	Not less than 3.5KN	Satisfactory
FLOW (mm)	3.45	2mm-4mm	Satisfactory
MARSHAL QUOTIENT	4.60	minimum 2.5 for unmodified and 3.0 for modified	Satisfactory
10% CRUMB RUBBER			
	RESULTS	AI SPECIFICATION	REMARKS
OBC (%)	5.50	5.0-8.0	
DENSITY	2.33		
VMA (%)	16.75	Minimum 13%	Satisfactory
VFA (%)	76.12	75.0-82.0	Satisfactory
STABILITY (KN)	16.50	Not less than 3.5KN	Satisfactory
FLOW (mm)	3.81	2mm-4mm	Satisfactory
MARSHAL QUOTIENT	4.33	minimum 2.5 for unmodified and 3.0 for modified	Satisfactory
20% CRUMB RUBBER			
	RESULTS	AI SPECIFICATION	REMARKS
OBC (%)	5.50	5.0-8.0	
DENSITY	2.27		
VMA (%)	16.43	Minimum 13%	Satisfactory
VFA (%)	75.60	75.0-82.0	Satisfactory
STABILITY (KN)	13.61	Not less than 3.5KN	Satisfactory
FLOW (mm)	3.95	2mm-4mm	Satisfactory
MARSHAL QUOTIENT	3.45	minimum 2.5 for unmodified and 3.0 for modified	Satisfactory
30% CRUMB RUBBER			
	RESULTS	AI SPECIFICATION	REMARKS
OBC (%)	6.80	5.0-8.0	
DENSITY	2.29		
VMA (%)	19.80	Minimum 13%	Satisfactory
VFA (%)	73.00	75.0-82.0	Not Satisfactory
STABILITY (KN)	10.50	Not less than 3.5KN	Satisfactory
FLOW (mm)	5.00	2mm-4mm	Not Satisfactory
MARSHAL QUOTIENT	2.10	minimum 2.5 for unmodified and 3.0 for modified	Not Satisfactory
40% CRUMB RUBBER			
	RESULTS	AI SPECIFICATION	REMARKS
OBC (%)	5.50	5.0-8.0	
DENSITY	2.16		
VMA (%)	15.81	Minimum 13%	Satisfactory
VFA (%)	74.82	75.0-82.0	Not Satisfactory
STABILITY (KN)	7.51	Not less than 3.5KN	Satisfactory
FLOW (mm)	4.32	2mm-4mm	Not Satisfactory
MARSHAL QUOTIENT	1.74	minimum 2.5 for unmodified and 3.0 for modified	Not Satisfactory
50% CRUMB RUBBER			
	RESULTS	AI SPECIFICATION	REMARKS
OBC (%)	5.50	5.0-8.0	
DENSITY	2.13		
VMA (%)	15.67	Minimum 13%	Satisfactory
VFA (%)	74.48	75.0-82.0	Not Satisfactory
STABILITY (KN)	5.93	Not less than 3.5KN	Satisfactory
FLOW (mm)	5.09	2mm-4mm	Not Satisfactory
MARSHAL QUOTIENT	1.17	minimum 2.5 for unmodified and 3.0 for modified	Not Satisfactory

Marshal quotient is the ratio of stability to flow and it indicates the strength and quality of the asphalt concrete. The results obtained, as presented in Table 5, show that the addition of crumb rubber up to 20%

presented satisfactory results on all levels and can conveniently be used to replace mineral fillers in the production of asphalt concrete. Beyond 20% crumb rubber, non-satisfactory results were obtained for VFA, Flow and Marshal quotient properties.

3.5 Performance Prediction Model Analysis

The performance modeling was conducted using regression analysis. MS Excel was employed in carrying out the regression analysis. The analysis was done in order to establish relationship between Marshall properties (Stability, Flow, VMA and VFA) considered as dependent variables and percentage crumb rubber, considered as independent variable, using the optimum bitumen content (OBC) of 5.5% and for the following conditions holding true:

i. Mix temperature of 150^{0}C
ii. Crumb rubber size of 0 - 0.075mm.
iii. 60/70 Pen Asphalt Binder
iv. Dense graded, wearing course HMA.

Figures 9-12 show the regression plot and curve of best fit for which the model was taken. R-squared, known as the coefficient of determination, shows how close the data are fitted to the regression line. The closer to 1 this value is, the better. The performance prediction model shows the relationship between the Marshal properties and percentage crumb rubber content.

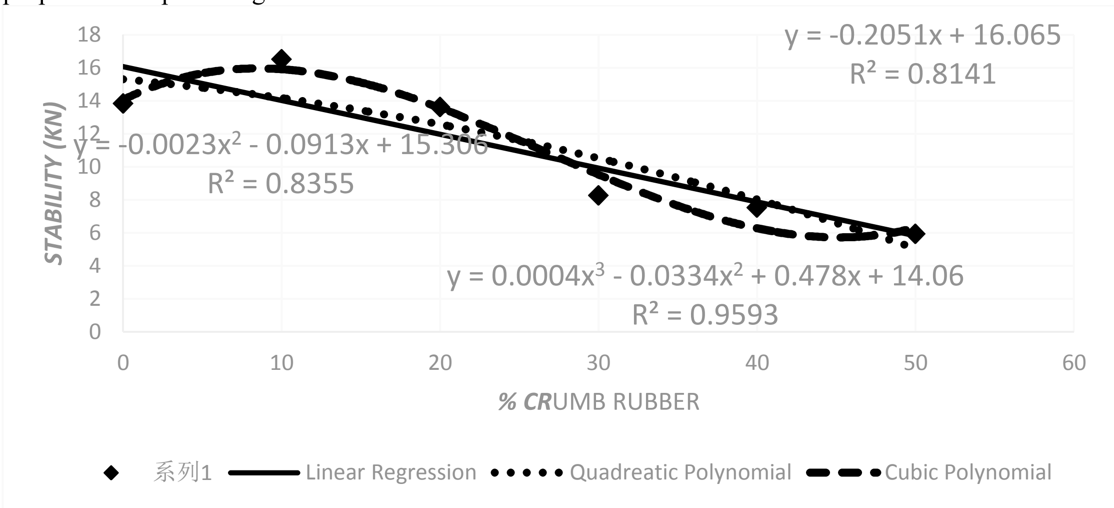


Figure 9: Regression Plot for Relationship between Marshall Stability and Crumb Rubber

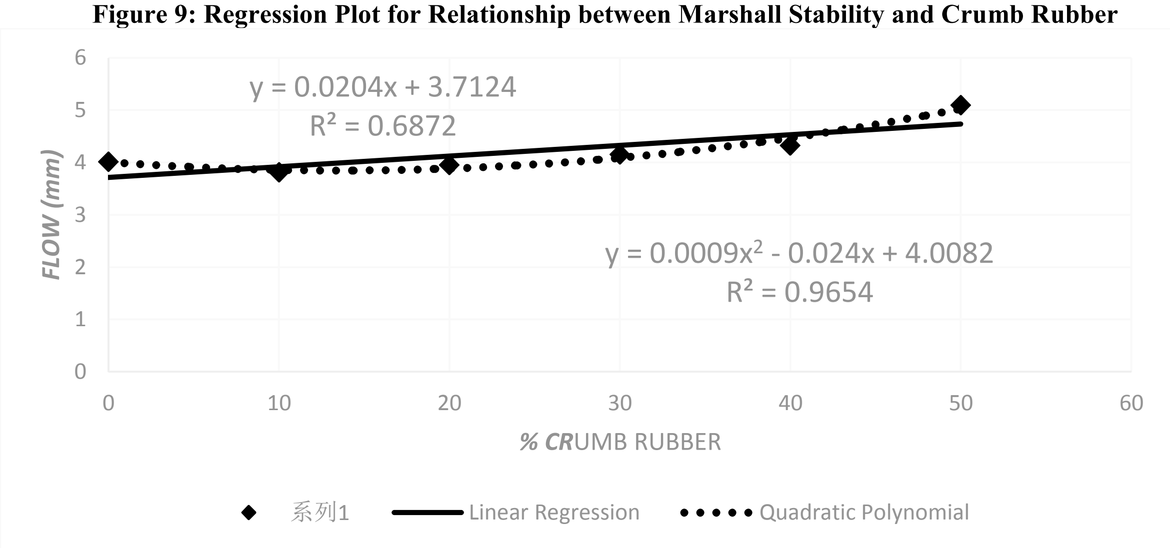


Figure 10: Regression Plot for Relationship between Marshall Flow and Crumb Rubber

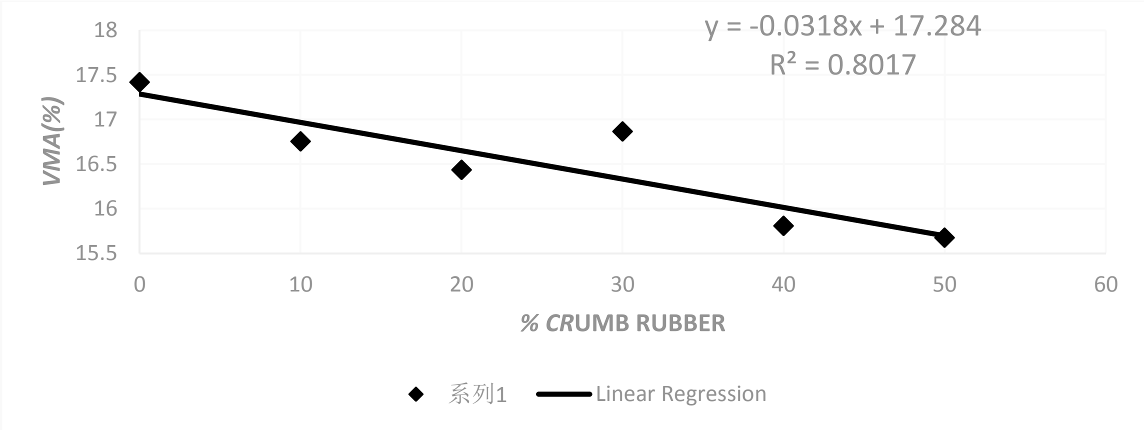


Figure 11: Regression Plot for Relationship between VMA and Crumb Rubber

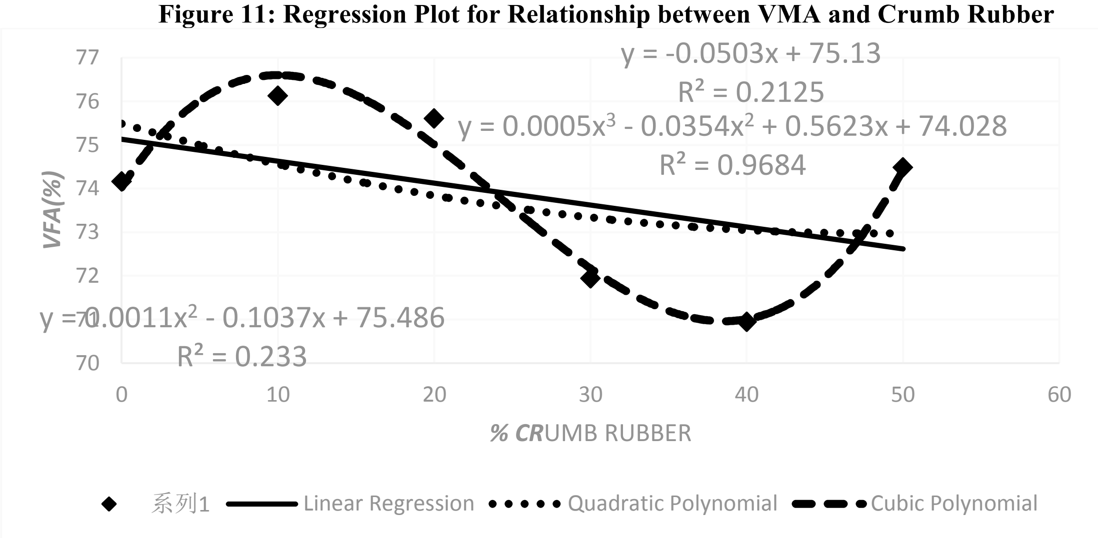


Figure 12: Regression Plot for Relationship between VFA and Crumb Rubber

The adopted performance prediction models of crumb rubber modified asphaltic wearing course are therefore summarized as follows:

Stability = $0.0004x^3 - 0.0334x^2 + 0.478x + 14.06$ ($R^2 = 0.9593$)
Flow = $0.009x^2 - 0.024x + 4.0082$ ($R^2 = 0.9654$)
VMA = $-0.0318x + 17.284$ ($R^2 = 0.8017$)
VFA = $0.0005x^3 - 0.0354x^2 + 0.5623x + 74.028$ ($R^2 = 0.9684$)

It is important to note that this performance prediction models do not however replace the need for laboratory tests.

3.6 Comparative Cost Analysis

This analysis is conducted to show the economic advantage of using crumb rubber in road construction, besides its environmental and engineering advantages. The cost of the materials was obtained through informal interviews with contractors and project managers in Nigeria. To determine the cost of wearing course surfacing material needed for construction, a road of length one kilometer (1km) and standard width 7.3 meters was used as basis for the analysis. Thickness of wearing course is taken as 50mm. The computation of the cost analysis is shown in Tables 6 and 7 while the summary of the cost analysis for the construction of the base material is shown in Table 8.

Table 6: Cost Analysis for Conventional Wearing Course Asphalt

ITEM	DESCRIPTION	QUANTITY FOR CONVENTIONAL ASHPALTIC CONCRETE	UNIT	QUANTITY	RATE (₦)	AMOUNT (₦)
	WEARING COURSE MATERIALS: 7.30 x 1000 x 0.05 = 365 m^3	**365 x 2.37 = 865.1 Tons.**	Tons	865.10		
1	Bitumen (60/70)		Tons.	52.77	274,000.00	14,459,281.40
2	Crushed Stones 3/8" (9.5mm)		Tons.	81.23	5,800.00	471,150.76
3	Crushed Stones 1/2" (12.5mm)		Tons.	162.47	5,800.00	942,301.52
4	Quarry Dust		Tons.	568.63	4,800.00	2,729,425.10
	TOTAL					**18,602,158.79**

Table 7: Cost Analysis for 20% Cr-Modified Wearing Course Asphalt

ITEM	DESCRIPTION	QUANTITY FOR 20% CR-MODIFIED ASPHALTIC CONCRETE	UNIT	QUANTITY	RATE (₦)	AMOUNT (₦)
	WEARING COURSE MATERIALS: 7.30 x 1000 x 0.05 = 365 m^3	**365 x 2.27 = 828.55 Tons.**	Tons	828.55		
1	Bitumen (60/70)		Tons.	50.54	274,000.00	13,848,384.70
2	Crushed Stones 3/8" (9.5mm)		Tons.	77.80	5,800.00	451,244.90
3	Crushed Stones 1/2" (12.5mm)		Tons.	155.60	5,800.00	902,489.80
4	Quarry Dust		Tons.	544.61	4,800.00	2,614,108.39
	TOTAL					**17,816,227.8**

Table 8: Summary of the Comparative Cost Analysis

Specimen	Production Cost (N)
Conventional Wearing Course Asphalt	**18,602,158.79**
20% CR-Modified Wearing Course Asphalt	**17,816,227.80**
Difference in Cost	**785,930.99**
% Difference in Cost/Km	**4.22%**

4. Conclusions and Recommendations

4.1 Conclusions

From the findings of the study, the following conclusions were made:

i. Asphalt concrete containing crumb rubber, up to 20% as partial substitution for mineral filler, satisfies the minimum structural requirement for flexible pavement construction.
ii. Asphalt concrete containing crumb rubber, beyond 20% as partial substitution for mineral filler, presented unsatisfactory results for VFA and Marshall flow; and therefore did not meet the minimum structural requirement for flexible pavement construction.
iii. Marshall Quotient decreased with increase in crumb rubber content.
iv. For a mix temperature of 150^0C, crumb rubber size of 0-0.075mm, 60/70 Pen bitumen and dense graded, wearing course HMA, the following performance prediction models apply:

Stability $= 0.0004x^3 - 0.0334x^2 + 0.478x + 14.06$ ($R^2 = 0.9593$)

Flow = $0.009x^2 - 0.024x + 4.0082$ ($R^2 = 0.9654$)
VMA = $-0.0318x + 17.284$ ($R^2 = 0.8017$)
VFA = $0.0005x^3 - 0.0354x^2 + 0.5623x + 74.028$ ($R^2 = 0.9684$)

v. From the comparative cost analysis, asphalt concrete with 20% crumb rubber content as partial substitution for mineral filler is cheaper than conventional asphalt concrete of equivalent Marshall properties.
vi. The comparative cost analysis shows a 4.22% savings in cost per kilometer of road.

4.2 Recommendations

The following recommendations are therefore made:

i. Proper waste disposal policies for waste tyres for their use in civil engineering practices should be developed.
ii. The use of crumb rubber in flexible road construction, up to 20%, showed satisfactory results; with 10% showing better results than conventional asphalt concrete. In addition, there is economic benefit to using it.
iii. Further studies into the possible use of crumb rubber in other aspects of civil engineering construction works should be encouraged.

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