PAVEMENT PERFORMANCE AND MODEL STUDIES WITH MODIFIED BITUMEN BINDER

Praveen Kumar P., Kiran Kumar B. V., Manjunatha S. and Subramanaya K. G.
Department of Civil Engineering, Government SKSJT Institute, Bangalore, Karnataka, India
E-Mail: praveenkumarputtappa@gmail.com

ABSTRACT

Flexible pavements experience premature deterioration due to several factors, such as high volumes of traffic, repeated wheel loads, overloading, adverse weather conditions, inferior quality of materials, and other related issues. One of the most commonly found types of distress is rutting, which severely affects pavement performance; hence, the prediction of rutting behaviour is crucial. Research has been done by adding various industrial wastes, chemicals, additives, and modifiers such as rubber, natural rubber, polymers, and waste plastic into the bitumen. These materials are expected to have a substantial impact on enhancing the strength, durability, and performance of pavement while simultaneously reducing the cost of construction. The present research deals with a laboratory investigation of bituminous mixes using both Marshall stability and rutting tests. The performance tests were carried out by Roller Compactor cum Rut Analyzer (RCRA) equipment and Finite Element (FE) analysis in ABAQUS. The experimental findings show that the modified bitumen exhibits 48% greater strength and 20% more resistance to rutting than the conventional bituminous mixes. The model analysis was successfully validated by experimental results. The findings of the research resulted in the development of a mathematical equation that helps to calculate in-service pavement rut depth.

Keywords: flexible pavement, modifiers, rutting, roller compactor cum rut analyzer (RCRA), finite element analysis, ABAQUS.

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INTRODUCTION

Flexible pavements are widely used in India as the predominant form of pavement. The composition of highway pavement is made up of multiple layers consisting of high-quality materials situated above the soil subgrade. The primary purpose of this construction is to effectively and securely transfer loads to the subgrade soil and distribute them over a larger area [1, 2, 3]. The pavement layers offer good skid resistance and a riding surface. Nevertheless, the pavement is subjected to early failures or distress caused by the repetitive application of wheel loads, overloading, and variations in environmental conditions [4, 5]. These factors severely reduce the lifespan of the pavement. Furthermore, flexible pavements are susceptible to a range of failures and distresses such as cracking, rutting, heaving, potholes, edge cracks, bleeding, and so on [6,7]. The rutting failure is an important structural design consideration for flexible pavements. Rutting forms on the pavement surface as longitudinal depressions all along the wheel path of the pavement surface, and it is a major concern for the safety of vehicles. The research studies have demonstrated that the characteristics and effectiveness of bituminous mixes can be improved through the incorporation of specific additives or combinations of additives referred to as "modifiers." The resulting bitumen, when combined with these modifiers, is commonly called "modified bitumen" [8, 9, 10]. The use of modified bitumen in pavement layers demonstrates a considerable enhancement in the overall lifespan of the pavement [11]. This practice contributes to the extension of the interval necessary for resurfacing, thereby significantly reducing the maintenance cost. Modified bitumen offers several advantages in road construction. These include its ability to withstand temperature fluctuations, resistance to deformation caused by heavy traffic loads, ability to postpone surface cracking and reflection cracking, and its strong bonding properties with aggregates and binders [12, 13]. Presently, plastics are widely utilized in several sectors, such as the packaging industry, agricultural sectors, building construction, automobiles, service sectors, etc. Research studies indicate that these plastics are non-biodegradable and take thousands of years to undergo degradation [14, 15, 16]. The disposal of plastic materials is also challenging due to their non-biodegradable nature, poses a significant environmental concern, and causes serious health complications for both humans and animals. Several studies have also shown that waste plastic may be utilized in a very efficient manner in pavement construction, which enhances the overall performance of pavements [17, 18].

The primary objective of this study is to perform Marshall Stability (ASTM D 6927-06, 1976) [19] and rutting performance tests in the laboratory on a blend of Bituminous Concrete Grade-II (BC Gr-II) and Dense Bituminous Macadam Grade-II (DBM Gr-II) mixes using both conventional and modified bitumen. The rutting tests were conducted using a Roller Compactor cum Rut Analyzer (RCRA), which has been specifically designed and developed for the research. The rutting behaviour of the pavement layers was predicted by finite element analysis using ABAQUS (Version 6.14-5) software [20], which resulted in the development of a mathematical equation to calculate in-service pavement rut depth.

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MATERIALS AND METHODS

Materials

The primary materials used in the present research are bituminous mixes, which consist of coarse aggregate, fine aggregate, bitumen binder of Viscosity Grade-30 (VG-30), and waste plastic-modified bitumen. Coarse aggregate consists of material passing through 20 mm and retained on a 4.75 mm Indian Standard (IS) sieve. Likewise, fine aggregate consists of material passing through a 4.75 mm sieve and being retained on a 0.075 mm IS sieve.

Marshall Method of Mixed Design

The Marshall method of mix design is commonly adopted to design bituminous mixes in the laboratory. The specimens are prepared following the guidelines outlined in the American Society of Testing Materials (ASTM D 6927) standard to assess their stability, flow, and Optimum Binder Content (OBC). A total of 1200 gm of aggregate are mixed suitably as per the obtained gradation. Aggregates are heated to a temperature in the range of 175^{o}C to 190^{o}C. Bitumen is heated to a temperature in the range of 121^{o}C to 145^{o}C, added to the aggregate, and thoroughly mixed at a temperature range of 154^{o}C to 160^{o}C. The prepared mix is subjected to compaction with 75 blows on each side of the specimen, with a temperature range of 138^{o}C to 149^{o}C. The specimens are allowed to cool at room temperature for 24 hours. The compacted specimens are carefully extruded from the mould, and their weight, height, and diameter are recorded, and corrections are applied if necessary. The specimens are submerged in the water bath for 30 minutes, maintaining a temperature of 60^{o}C. Then they are subjected to the Marshall Stability test to find stability, density, volume of air voids, and various other parameters. The optimum binder content is determined to correspond to 4% air voids, as specified by MoRT&H [21]. The procedure is repeated with conventional and polymer modified bitumen at various percentages, starting from 4.0%, 4.25%, 4.50%, and 4.75%, etc., until 6.0%.

Roller Compactor cum Rut Analyzer (RCRA)

The Roller Compactor cum Rut analyzer equipment as shown in Figure-1 mainly consists of a display board, a metallic roller compactor, metallic moulds, a rubber-rutting wheel, a loading frame, pressure controllers, etc. The unique feature of the equipment is that it has different sizes of moulds of varying heights, which can accommodate the pavement crust thickness of up to one meters. The present methodology involves the casting of specimens by considering a California Bearing Ratio (CBR) of 5% and a design life of 10 million standard axles (msa). The pavement crust thickness is built by the parameters mentioned in Table-1 (IRC 37-2018) [22], and the rutting test is performed on a combination of bituminous mixes, namely, BC Gr-II is built as a surface course and DBM Gr-II as a binder course layer. Both mixes were prepared by the Job Mix Formula (JMF) and Optimum Binder Content (OBC). The weight of each bituminous mixture required to attain the appropriate thickness is determined. Coarse aggregate, fine aggregate, bitumen, and modified bitumen binder were heated to a temperature of 140°C to 160°C. The mixture is meticulously blended in the pan and thereafter poured into the casting mould of size 640x275x300 mm (length x breadth x height). The mould is properly placed in the compactor of the Roller Compactor cum Rut Analyzer (RCRA) equipment and compacted to attain the desired thickness. Once the specimen reaches the desired thickness, it is subjected to rutting by applying a load that can induce a contact pressure of 0.56 MPa (IRC 37-2018). The number of passes and respective rut depths are automatically recorded in the data acquisition system of the equipment. The test is repeated for different specimens prepared with bitumen and waste plastic-modified bitumen content. The rutting specimens cast in the laboratory before and after undergoing rutting are shown in Figures 2 and 3, respectively.

Table-1. Pavement catalogue for 5% CBR value and 10msa design life.

CBR (%)	Traffic load (msa)	Pavement thickness constructed in RCRA (mm)		
		Surface course	Binder course	Base course
5	10	40	80	250

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Figure-1. Roller Compactor cum Rut Analyzer (RCRA).

Figure-2. Specimen before rutting.

Figure-3. Specimen after rutting.

Finite Element (FE) Analysis by Using ABAQUS Software

The present study employs Finite Element (FE) analysis, utilizing the ABAQUS software. The finite element modeling method is widely acknowledged as a highly effective approach for investigating the structural behavior of multi-layered pavement systems [23, 24]. The study encompasses both three-dimensional and two-dimensional, or axisymmetric, components. Finite Element (FE) models are employed to replicate the responses to different structural engineering challenges. These models consider various directional aspects of stress. It is widely accepted in the field that bituminous layers exhibit viscoelastic properties [25, 26]. The utilization of 3D modeling enables the anticipation of rutting phenomena on the surfaces of flexible pavements. The ABAQUS software allows for the specification of load magnitude, position, and direction using the load module [27, 28]. This enables the simulation of moving loads that vary in both time and location. The purpose of this simulation is to evaluate the effects of rutting caused by each pass of a wheel load on the pavement. The model relies on two crucial input parameters, namely the modulus of elasticity (E) and Poisson's ratio [29]. The input values are adopted as per IRC 37-2018 and are shown in Table-2. The dimensions of each component in the finite element model are determined based on a convergent analysis. The details of layer creation in ABAQUS are shown in Figure-4.

Table-2. Input parameters in ABAQUS.

Type of Material	Elastic Modulus (E), MPa	Poisson's Ratio
Surface Course	2000	0.35
Binder Course	2000	0.35
Granular Base Course	450	0.35

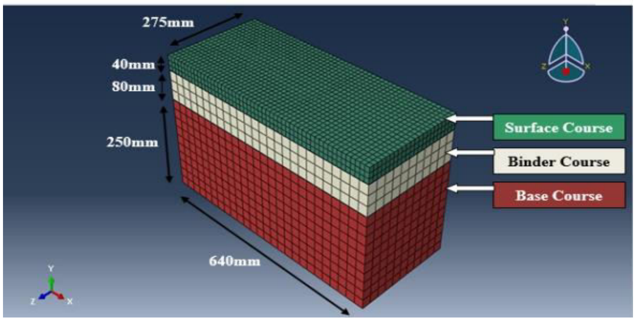

Figure-4. Layer creation in ABAQUS.

The Outline of the Approach Employed for the Present Research is as Follows

The selected materials were subjected to preliminary testing by the relevant requirements set by the Ministry of Road Transport and Highways (MoRT&H, 2013) specifications to determine their suitability for the investigation. The Job Mix Formula (JMF) was arrived at through a process of trial and error to achieve the required design gradation for BC Gr-II and DBM Gr-II mixes and is shown in Table-3. By the American Standards of Testing Materials (ASTM D 6927-06), Marshall specimens were cast in the laboratory using VG-30 and waste plastic-modified bitumen to determine the Optimum Binder Content (OBC) and other relevant parameters. Rutting specimens were cast in the laboratory using conventional bitumen and modified bituminous binders for the pavement layers with an effective CBR value of 5% and 10 msa design life. A Finite Element (FE) model was created using the ABAQUS software in line with the

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designed pavement crust thickness. Finally, a ‘Shift Factor’ is arrived at using a mathematical equation to validate the results of the experimental method with the FE model.

RESULTS AND DISCUSSIONS

The results of the Marshall Stability test on BC Gr-II and DBM Gr-II mixes prepared with conventional and modified bitumen binders satisfy the requirements of the specifications as shown in Table-4. The optimum binder content of waste plastic-modified bitumen is 0.4% less than that of the conventional bituminous mix. This value is in line with the earlier research findings and helps in a considerable reduction in the cost of construction on large road projects. The findings also demonstrate that the use of modified binders considerably enhances the Marshall Stability and bulk density of the bituminous mixes. Furthermore, the addition of waste plastic reduces the flow value in the mix, making the pavement surface less susceptible to temperature and enhancing its durability. The waste plastic-modified bituminous mix exhibited 48% more strength than the conventional bituminous mix. The other parameters, such as volume of voids, voids in mineral aggregate, and voids filled with bitumen, satisfied the minimum requirements as stipulated by MoRT&H. Furthermore, the waste plastic-modified bitumen sustains 20% more rutting than the conventional bituminous mixes. The rutting values obtained for the bituminous mixes are shown in Table-5.

Table-3. Job Mix Formula (JMF) for bituminous mixes.

Type of Bituminous Mix	Aggregate (%)			Optimum Binder content (OBC), %
	20mm & down size	12.5mm & downsize	4.75mm & downsize	
BC Gr-II (conventional bitumen)	10	45	45	5.60
BC Gr-II (with waste plastic modified bitumen)	10	45	45	5.60
DBM Gr- II (conventional bitumen)	20	50	30	5.20

Table-4. Marshall Properties of bituminous mix.

Marshall Property	BC Gr-II Mix		DBM Gr-II With VG 30
	With VG 30	With waste plastic-modified bitumen	
Optimum Binder Content (OBC), %	5.60	5.60	5.10
Marshall Stability, kg	2245	2810	1190
Flow Value, mm	3.87	3.65	3.85
Bulk Density, gm/cc	2.32	2.36	2.26
Volume of Air Voids, (Vv), %	3.73	3.65	3.96
Voids in Mineral Aggregate (VMA), %	15.99	15.17	16.70
Voids Filled with Bitumen (VFB), %	72.43	71.26	81.30

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Table-5. Rutting results with VG 30 and waste plastic modified bitumen.

Rut Depth (mm)	Number of passes in RCRA	
	BC Gr-II with VG 30	BC Gr-II with waste plastic-modified bitumen
0	0	0
2	6326	8140
4	11444	13467
6	15762	18876
8	18005	20987
10	20954	23111
12	21999	25422
14	24308	27842
16	26995	30320
18	28780	33414
20	28890	35050

In the FE model analysis, the different pavement layers were analyzed, and the deformation values were obtained, as shown in Figure-5. It is observed from Figure-6 that the maximum deformation or rut depth occurs nearly at the mid-depth of the model specimen, i.e., at 137.594 mm. Graphs are plotted indicating the number of passes sustained v/s rut depth both in RCRA and in ABAQUS and are shown in Figures 7 and 8, respectively.

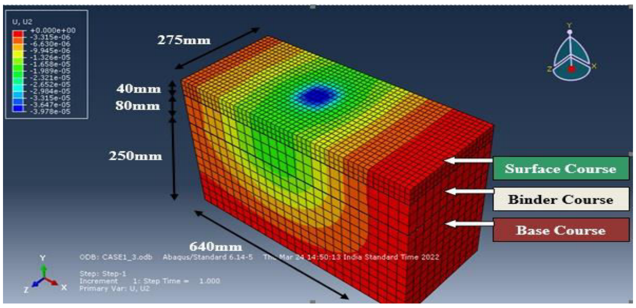

Figure-5. Results of deformation.

Figure-6. Displacement v/s distance in ABAQUS.

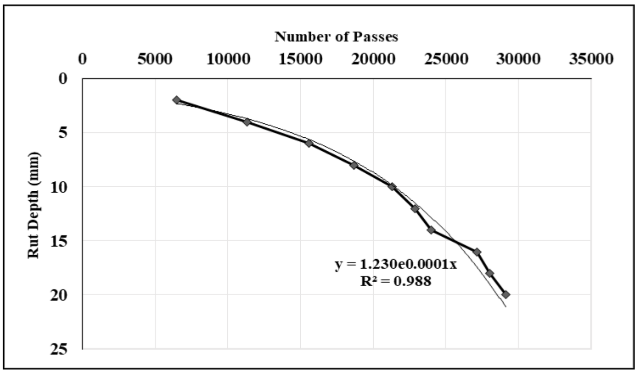

Figure-7. Rut depth v/s number of passes in RCRA.

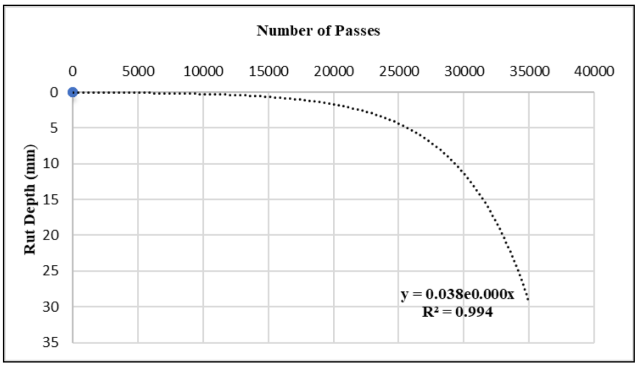

Figure-8. Rut depth v/s number of passes in ABAQUS.

Based on research findings, a mathematical equation for rut depth is obtained and shown in eqn. (1). Finally, a shift factor for rut depth is obtained based on the research findings and is shown in Table-6.

The obtained exponential equation for rut depth, (mm)

$$y = ae^{bN} \tag{1}$$

Where,
y represents rut depth in mm
a and b are constants,
e is exponential constant
N represents the number of passes (represented as x in the graph)

Table-6. Values of shift factor.

Parameters	Value of 'a'	Value of 'b'	Value of Variance	Shift Factor
Values from ABAQUS Modeling	0.0385	0.0002	0.0031270	**320**
Values from RCRA for BC Gr-II Mix	1.2304	0.00010	0.0027889	**359**
Values from RCRA, for BC Gr-II mix with modified bitumen	1.219	0.00008	0.003496	**312**

From Table-6, it is observed that there is a very close relationship between FE model analysis and the experimental methods. i.e., 320 in the case of FE model analysis, 359 and 312 in the case of RCRA with conventional and modified bitumen, thus successfully validating the research. The shift factor values estimate the rutting values of the in-service pavements. As an example, to estimate the number of passes required to undergo 20 mm rut depth in the field, multiply the number of passes obtained in the experimental method by shift factor values. In summary, the previous research and the present study employ different materials and methodologies to enhance pavement performance and predict rutting. The present study goes one step forward in the prediction of rutting by comparing the results of experimental methods with those of FE modeling. The studies successfully validated the research by suggesting a mathematical equation and a shift factor to predict in-service rutting values.

CONCLUSIONS

The present research examines the performance of conventional bituminous mixes and modified bituminous mixes by conducting various tests. The studies successfully demonstrated that the use of modified bitumen significantly enhances the strength and reduces the flow value in the bituminous mixes. This makes the pavement surface less susceptible to temperature changes. In addition, the use of modified bitumen reduces the cost of construction, thus providing a viable solution for waste disposal problems and achieving sustainability in road construction.

The use of modified bitumen in the bituminous mixes significantly enhances the rutting resistance, as this helps to extend the service life of the pavement and the time period required for resurfacing the pavement surface. The research successfully validated the performance of the pavement against rutting by conducting experimental and model studies and developing a mathematical equation and shift factor values. These can be used to estimate the in-service rutting values.

The results obtained in the present research are also supported by the previous research findings. The controlled conditions and boundary conditions may affect the outcome of the experimental investigation. Some of the factors that affect rutting in real-world applications, such as temperature, moisture, and climatic conditions, were not considered during the experimentation. To promote sustainability in road construction, it is advisable to investigate innovative techniques and include various parameters in further research programs.

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