Effects of Bitumen Content on the Quality of Asphalt Used for the Construction of Flexible Pavements

Efectele conţinutului de bitum asupra calităţii asfaltului utilizat pentru construcţia pavejelor flexibile

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Abstract: *Road pavements in Nigeria and other developing regions are often faced with premature failures due to suboptimal asphalt mix designs, particularly related to bitumen content (5%, 6%, 7% and 8%) as this affects the mechanical and durability properties of asphalt used for flexible pavement construction. Laboratory tests, including penetration, ductility, viscosity, flash and fire points, Marshall Stability, flow, bulk density, air voids and drying shrinkage tests were conducted. The results indicate that an optimum bitumen content of approximately 6.67% provides the best balance of stability, density and durability. Higher contents lead to excessive deformation and rutting, while lower contents result in inadequate cohesion and strength. These findings highlight the importance of adequate mix design to enhance pavement performance and longevity in similar conditions*

Keywords: bitumen content, asphalt, flexible pavement, Marshall Stability, optimum

1. Introduction

The transportation industry is an important aspect of the economic growth of any given country, since road systems contribute to commerce, trade and social interaction [1]. Flexible pavements are the most common types of pavements because of their low cost of construction, maintenance and their ability to accommodate different traffic demands [2]. Hot mix asphalt, comprising aggregates and bitumen as a binding agent, is the main material used in flexible pavement construction. The composition of asphalt pavements and bitumen content are the key factors that determine the performance of these materials and durability of asphalt pavements [3].

The surface layer of the pavement structure is the most important layer as it is expected to provide the ultimate function of an economic, safe and comfortable riding surface to users thereby protecting the sub-structure layers from infiltration of water and foreign materials and distributing stresses from axle loads satisfactorily to layers beneath without comprising durability [4].

Bitumen is a viscoelastic material that provides cohesion within asphalt mixtures, ensuring structural stability and resistance to external loads [5]. However, variations in bitumen content can significantly affect pavement performance. A low bitumen content results in weak bonding between aggregates, leading to high air voids, premature cracking and raveling. Conversely, excessive bitumen content can cause bleeding, rutting and reduced resistance. Thus, determining the optimal bitumen content is essential for achieving a balance between durability and flexibility in asphalt pavements.

In Nigeria, road infrastructure continues to face challenges such as premature failure, potholes and frequent maintenance due to poor asphalt mix design. Several roads deteriorate within a few years of construction, causing economic losses and safety hazards [6]. This study assesses the effects of bitumen content on the quality of asphalt used in flexible pavements construction, with a focus to improving mix design for better road performance.

2. Methodology

This study adopts an experimental research design, which is appropriate for evaluating the effects of varying bitumen content on the quality of asphalt used in the construction of flexible pavements. The experimental design involves the laboratory preparation and testing of asphalt samples with different bitumen contents to assess their mechanical and durability properties. The results obtained from these tests will provide empirical evidence on the optimal bitumen content required to achieve high-quality asphalt pavement [7].

2.1 Sample Collection and Preparation

The materials used for this study include bitumen and aggregates (coarse and fine) and filler material. The bitumen was sourced from a bitumen supplier in Omuo-Ekiti, Ekiti State, Nigeria. The grade of the bitumen used was 60/70 grade. The aggregates (granite and stone dust) were sourced from a sales point along Akure-Ijare road. The filler material is a modified material made from combining crushed ceramic tiles sourced locally and very fine stone dust.

Asphalt samples were prepared with varying bitumen contents to determine its impact on asphalt performance. The bitumen content variations were set at 5%, 6%, 7% and 8% by weight of the total mix. These percentages were chosen based on Federal Ministry of Works (FMW 2007) standards [8]. The aggregates and bitumen were thoroughly mixed under controlled conditions to ensure even distribution and proper coating of the aggregates, creating consistent and reliable samples for testing.

The asphalt mixtures were shaped into cylindrical specimens using a Marshall compactor, ensuring they were ready for testing. Compaction was carried out following standard protocols to guarantee consistent density and structural integrity across all samples. Once compacted, the specimens were left to cure properly before being subjected to laboratory tests. This step ensures the samples are stable and representative of real-world conditions for accurate evaluation.

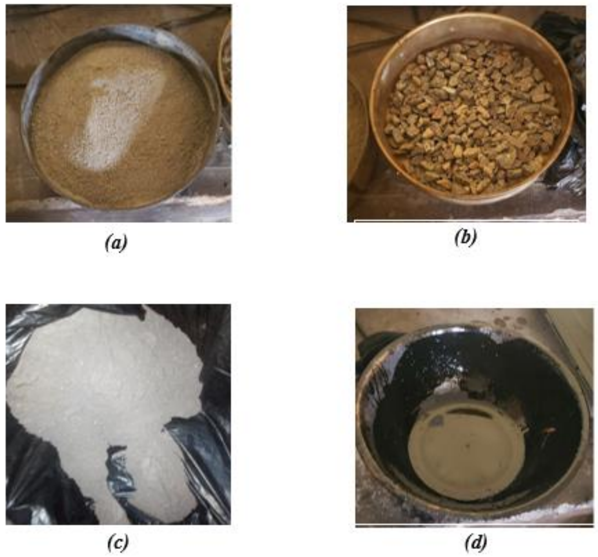

Figure 1 (a) to (d): Materials used in preparing the asphalt samples. (a) stone dust (b) granite (c) filler material (d) bitumen

Figure 2: Cast Asphalt Samples

2.2 Laboratory Tests

All laboratory tests were carried out at the Transport and Materials Laboratory in the Department of Civil and Environmental Engineering, Federal University of Technology Akure (FUTA), Akure, Nigeria. To evaluate the effects of bitumen content on asphalt quality, the following laboratory tests were conducted:

2.2.1 Bitumen Tests

- Penetration Test: The penetration test evaluates the hardness or softness of bitumen by measuring how far a standard needle can penetrate into it under controlled conditions. The test is conducted at 25°C with a penetrometer having a 100-gram weight applied for 5 seconds. The depth of penetration is measured in tenths of a millimeter [9].
- Viscosity Test: The viscosity test checks how easily bitumen flows at different temperatures. It is usually carried out at 60°C (representing road temperature) and 135°C (representing mixing and compaction temperature). The test is conducted using a viscometer, which measures how much time it takes for bitumen to flow through a standard orifice [10].
- Flash and Fire Point Test: The flash and fire point test determines the temperatures at which bitumen begins to emit ignitable vapors (flash point) and sustain combustion (fire point) when heated in a

controlled manner. In the Pensky-Martens closed-cup apparatus method, a sample of binder is placed in a sealed cup that is gradually heated (typically at 5-6°C/min) while a standardized ignition source is introduced at regular temperature intervals [11].

- Ductility Test: The ductility test measures how far bitumen can be stretched before breaking, indicating its ability to form a continuous film and resist cracking. It involves heating bitumen to a fluid state and pouring it into a briquette mould. The filled mould is cooled in air for 30-40 minutes, then placed in water bath at a standard temperature for a specified time [12].
- Specific Gravity Test: The specific gravity test determines the density of binder relative to water by using a calibrated pycnometer at 25°C: after heating the bitumen, the empty pycnometer is weighed (M_1), then filled with water (M_2), partly filled with bitumen and submerged (M_3) and finally filled with bitumen topped to the mark with water (M_4). The specific gravity is then calculated as shown in equation 1 [13].

2.2.2 Asphalt Mechanical Tests

- Marshall Stability Test: Marshall Stability refers to the maximum load an asphalt sample can withstand before failure, while flow measures the extent of deformation under loading. The Marshall Stability Test is essential in determining the strength and stability of asphalt mixtures. It involves loading a compacted asphalt specimen until failure to measure its maximum load-bearing capacity [14].
- Durability Tests: Durability tests assess how well asphalt can withstand long-term exposure to environmental conditions such as temperature changes, moisture and oxidation. Durability tests were conducted to assess the resistance of asphalt to weathering and aging. These tests simulate long-term exposure to environmental conditions such as moisture, temperature variations and oxidation [15].

3 Results and Discussions

The fundamental properties of the bitumen were evaluated to establish a baseline for mix design and to assess its conformity with typical specification requirements.

3.1 Analysis of the Bitumen Properties

3.1.1 Penetration Test

The penetration test measures the hardness of bitumen by measuring the depth (in tenths of a millimeter) a standard needle penetrates under specified conditions. The average penetration value of 69.3 as shown in table 1 places the bitumen in the 60/70 grade. The results indicate that the bitumen has a balanced consistency and can resist deformation under loading while maintaining flexibility [9].

Table 1

Penetration Test values

S/N	First trial (d-mm)	Second trial (d-mm)
1	75.80	66.90
2	76.20	67.40
3	69.20	60.30
AVG		**69.3**

3.1.2 Ductility Test

Ductility measures the distance a standard briquette of bitumen can be elongated before breaking, indicating its tensile properties and internal cohesion. The average ductility value recorded as shown in table 2 suggests that the bitumen is relatively highly flexible and capable of withstanding significant elongation before failure. According to standard specifications, ductility value should be ≥100cm, which indicates good quality for most paving applications [12].

Table 2

Ductility Test Results

S/N	Ductility Tests (cm)
1	88.00
2	84.10
3	137.20
AVG	**103.10**

3.1.3 Flash and Fire Point Tests

The flash point is the lowest temperature at which the binder produces ignitable vapors, while the fire point is the lowest temperature at which sustained combustion occurs. These are critical safety parameters for handling and mixing. The flash point, as shown table 3, is relatively low for bitumen, particularly for grade 60/70 bitumen. According to standard specifications, a minimum flash point of 220°C is required for safety during storage, transportation and hot-mix asphalt production. The flash point suggests that the bitumen may release volatile vapors at a lower temperature, increasing the risk of ignition during heating process [11].

Table 3

Flash and fire point Test Results

S/N	Flash point (^{0}C)	Fire point (^{0}C)
First trial	172.3	221.2
Second trial	167.5	240.0
AVG	**169.9**	**230.6**

3.1.4 Viscosity Tests

Viscosity measures the bitumen’s resistance to flow. The average viscosity value, as shown in table 4 suggests that the bitumen is relatively resistant to flow within a 60/70 grade, which can enhance resistance to rutting, especially in hot climates [10].

Table 4

Viscosity Test Results

S/N	Viscosity Reading (mPa.s)
1	3442.00
2	3360.00
3	3259.00

AVG	3353.67

3.1.5 Specific Gravity Test

The specific gravity of the bitumen was determined using a pycnometer and the following weights:
Weight of empty bottle $M_1 = 63.12g$
Weight of bottle + Sample $M_2 = 87.13g$
Weight of bottle + sample + water $M_3 = 122.71g$
Weight of bottle + water = $M_4 = 122.35g$

Specific gravity (SG) = $\frac{M_2 - M_1}{(M_4 - M_1) - (M_3 - M_2)}$ (1)

$$SG = \frac{87.30 - 63.12}{(122.35 - 63.12) - (122.71 - 87.30)}$$

SG =1.02

3.2 Marshall Mix Design Analysis for Optimum Bitumen Content

The Marshall mix design method was employed to determine the optimum content by evaluating key performance parameters across a range of bitumen contents (5% to 8%). The relationship between bitumen content and these properties (shown in table 5) is fundamental in understanding mix behaviors [14].

Table 5

Relationship between bitumen percentages and stability and flow values

% bitumen	Dry weight (g)	Wet weight (g)	Submerged weight	Stability in kg	Flow in mm
5%	984.58	992.77	562.25	22.91	3.79
6%	1007.70	1013.73	581.45	18.65	3.91
7%	1035.32	1040.10	586.17	23.19	6.06
8%	1058.30	1063.25	601.23	20.06	5.94

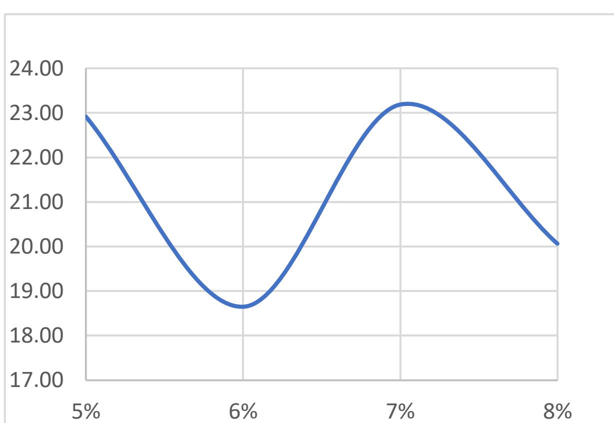

Figure 2: Graph of stability against bitumen percentages

The stability values, as in figure 1, demonstrate a non-linear relationship, initially decreasing from 5% to 6% before peaking at 23.19 kg for the 7% mix and then decreasing at 8%. This occurs because at low bitumen contents (i.e. 5%), the mix is lean and incomplete coating of aggregates leads to lower cohesion and stability. As bitumen increases to 7%, it provides optimal coating and lubrication during compaction, resulting in a strong, cohesive matrix that maximizes internal friction and stability. At high bitumen contents (i.e. 8%), excess binder acts as a lubricant, pushing aggregates particles apart and reducing inter-particle friction and stability [14].

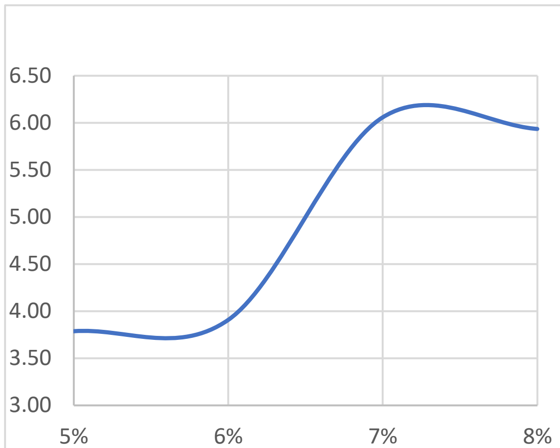

Figure 3: Graph of flow against bitumen percentages

The flow values, as shown in figure 2, indicate a significant increase after 6% bitumen content. The rise from 3.91 mm at 6% bitumen content to 6.06 mm at 7% bitumen content indicates a transition from a stiff and elastic mix to a more plastic and deformable one. According to standard specification, the typical acceptable flow range is 2-4 mm. The 7% and 8% mixes exceed this limit, indicating a potential for excessive plastic deformation and rutting under traffic [14].

Calculation of Bulk density

$$\text{Specific Gravity } (G_{mb}) = \frac{\text{dry mass}}{\text{saturated surface dry mass} - \text{mass of sample submerged in water}} \quad (2)$$

For 5%, $G_{mb} = \frac{984.58}{992.77-562.25} = 2.29$

For 6%, $G_{mb} = \frac{1007.70}{1013.73-581.45} = 2.33$

For 7%, $G_{mb} = \frac{1035.32}{1040.10-586.17} = 2.28$

For 8%, $G_{mb} = \frac{1058.30}{1063.25-601.23} = 2.29$

Table 6

Relationship between Bulk density and varying bitumen contents.

% bitumen	Bulk Specific Gravity
5%	2.29

6%	2.33
7%	2.28
8%	2.29

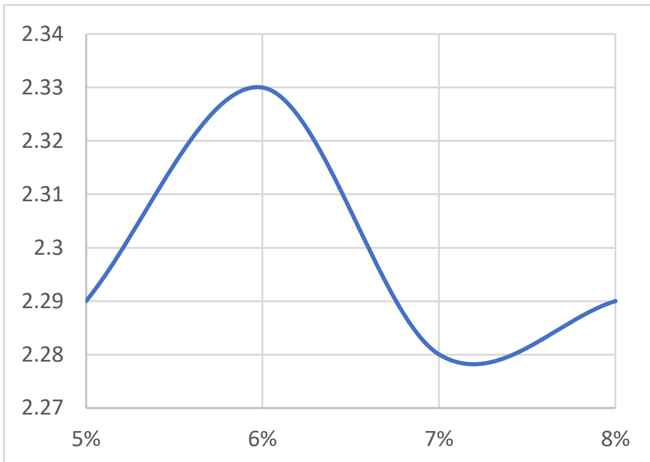

Figure 4: Graph of bulk density against bitumen percentages

The bulk specific gravity (G_{mb}), representing the bulk density (as in figure 3) of the compacted mix shows a clear peak at 6% bitumen content. This occurs because up to 6%, the additional bitumen provides better lubrication, allowing aggregate particles to be arranged into a denser configuration during compaction. Beyond 6%, the volume of bitumen exceeds the void space available in the mineral aggregates' matrix. Since bitumen is less dense than aggregate, the overall mix density begins to decrease.

Calculation of Percentage Air Voids

$$P_a = \frac{Gmm - Gmb}{Gmm} \times 100 \tag{3}$$

where

P_a - percentage air voids in in the asphalt samples
G_{mm} - maximum specific gravity of the asphalt samples
G_{mb} - bulk specific gravity of the asphalt samples

But maximum specific gravity (G_{mm}) is given as

$$G_{mm} = \frac{100}{\left(\frac{Ps}{Gse}\right) + \left(\frac{Pb}{Gb}\right)} \tag{4}$$

where

G_{mm} - maximum specific gravity of the asphalt samples
P_s - Percentage by weight if aggregates
P_b - Percentage by weight of bitumen
G_{se} - Effective specific gravity of the aggregates (assumed to be constant for different asphalt contents

G_b - Specific gravity of asphalt

$P_s = 95\%$

$G_{se} = 2.7$ [13]

$P_b = 5\%$ to 8%

$G_b = 1.02$ (from laboratory tests)

$\therefore$ For 5%, $G_{mm} = \frac{100}{\left(\frac{95}{2.7}\right)+\left(\frac{5}{1.02}\right)} = 2.495$

For 6%, $G_{mm} = \frac{100}{\left(\frac{95}{2.7}\right)+\left(\frac{6}{1.02}\right)} = 2.435$

For 7%, $G_{mm} = \frac{100}{\left(\frac{95}{2.7}\right)+\left(\frac{7}{1.02}\right)} = 2.378$

For 8%, $G_{mm} = \frac{100}{\left(\frac{95}{2.7}\right)+\left(\frac{8}{1.02}\right)} = 2.324$

$$\therefore \mathbf{P_a} = \frac{Gmm-Gmb}{Gmm} \times \mathbf{100} \qquad (5)$$

At 5%, $P_a = \frac{2.495-2.29}{2.495} \times 100 = 8.032\%$

At 6%, $P_a = \frac{2.435-2.33}{2.435} \times 100 = 4.312\%$

At 7%, $P_a = \frac{2.378-2.28}{2.28} \times 100 = 4.121\%$

At 8%, $P_a = \frac{2.324-2.29}{2.324} \times 100 = 1.463\%$

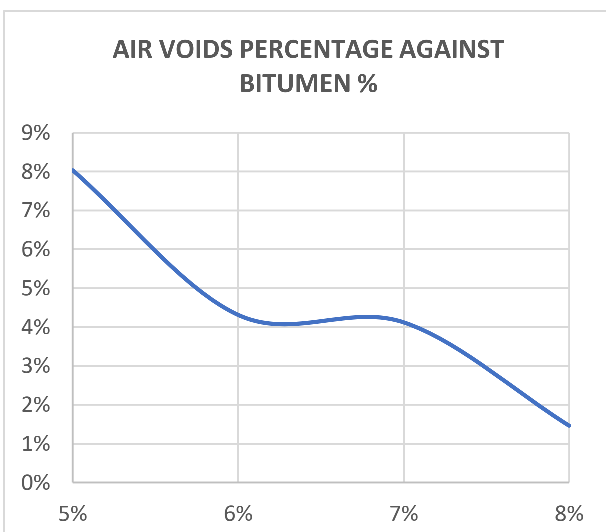

Figure 5: Graph of percentage air voids against bitumen percentages

The percentage of air voids (VTM), as shown in figure 3, exhibits a steady, inverse relationship with bitumen content. This is a result of the additional binder progressively filling the voids between the compacted aggregates particles. According to standard specification, the target air void percentage is 4%, which is achieved at approximately 7% bitumen content. Air void below 3% can lead to bleeding and rutting, as seen in the 8% mix [15].

Calculation of Optimum Bitumen Content

Optimum Bitumen Content

$$= \frac{Optimum\ Marshall\ stability + Optimum\ bulk\ density + 4\%\ air\ voids}{3} \quad (6)$$

$$= \frac{7 + 6 + 7}{3}$$

$$= \frac{20}{3}$$

= 6.67%

3.3 Analysis of Drying Shrinkage Test

Table 7

Drying shrinkage values of the varying bitumen content

% bitumen	after casting			after 7 days				after 28 days			
	diameter (cm)	height (cm)	Volume (cm3)	diameter (cm)	height (cm)	Volume (cm3)	% volume change	diameter (cm)	height (cm)	Volume (cm3)	% volume change
5%	10.20	5.92	483.80	10.13	5.90	475.57	-1.70%	10.12	5.82	468.20	-3.23%
6%	10.23	5.92	486.65	10.21	5.90	483.11	-0.73%	10.20	5.62	459.29	-5.62%
7%	10.18	6.27	510.40	10.05	6.21	492.69	-3.47%	10.00	6.03	473.66	-7.20%
8%	10.27	6.30	521.95	10.12	6.09	489.92	-6.14%	10.05	6.00	476.02	-8.80%

All samples shrank over the 28-day period. This is because as the bitumen cures, volatile materials evaporate and the materials consolidate under their own weight. The highest total volume loss occurs at 6% bitumen content. Its significant height loss is a major red flag for stability. At 8% bitumen content, the volume loss was highest overall, indicating poor initial stability. At 7% bitumen content, the mix shrank more uniformly and in a stable manner; its deformation was mostly complete after the first 7 days, showing good curing stabilization. At 5% bitumen content, the mix showed gradual but consistent shrinkage, which may be as a result of insufficient binder content.

In summary, it can be deduced that the optimal bitumen content for achieving the best balance of initial workability and long-term dimensional stability of the mix was at 7%.

4. Conclusions

This study investigated the effects of bitumen content (5%, 6%, 7% and 8%) on the properties of asphalt for flexible pavement construction using the Mashall mix design method. Based on the laboratory experiments and subsequent analysis, the following conclusions are drawn [7]:

i. Determination of Optimum Bitumen Content (OBC): The study established the optimum bitumen content (OBC) for the specific materials and conditions tested. The OBC was calculated to be 6.67%, derived from the optimum values for Marshall Stability, Bulk Density and 4% Air Voids. This value falls within the range specified by the Federal Ministry of Works (FMW) Nigeria standards (i.e. 5.0% -8.0%) and represents the binder proportion that provides the best balance of strength, density and durability [8].

ii. Effects on Mechanical Properties: The bitumen content significantly influenced the mechanical properties of the asphalt mix. Marshall Stability, which indicates load-bearing capacity, peaked at 7% bitumen content. However, the flow value at this percentage bitumen content exceeded the acceptable standard range (i.e. 2-4mm), indicating excessive deformation. At 6% bitumen content, the mix showed a better balance of adequate stability and acceptable flow, highlighting the trade-off between strength and flexibility [14].

iii. Effects on Volumetric Properties: The bulk specific gravity, which is related to density and compactness, was highest at 6% bitumen content. The percentage of air voids (Pa) decreased progressively with increasing bitumen content. The 4% air void criterion was met at approximately 7% bitumen content. This demonstrates that volumetric properties are highly sensitive to binder content and are critical for determining the OBC [13].

iv. Dimensional Stability: The drying shrinkage test revealed that all samples experienced volume reduction over 28 days. The mix with 7% bitumen content demonstrated the most uniform and stable curing behavior. This suggests that the OBC provides not only good mechanical and volumetric properties but also superior long-term dimensional stability, reducing the potential for cracking.

v. Bitumen Binder Quality: The tests on the bitumen with 60/70 penetration grade showed a high ductility value (103.10cm), indicating good flexibility and cohesion. However, the flash point (169.9°C) was below the standard safety threshold (i.e. 220°C according to ASTM standards), necessitating strict temperature control during handling and production to prevent fire hazards [11].

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