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Dynamic Modulus and Fatigue Life of Corn Starch Modified Bitumen in Asphalt Concrete Pavement

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Abstract: *Harnessing the potential of unconventional materials for a sustainable pavement infrastructure is not new; hence, this research explores the effect of Corn Starch (CS) on the dynamic modulus and fatigue resistance properties of asphalt concrete to serve as a basis for using such materials for asphalt concrete production. An experimental procedure using the Marshal Mix design method was adopted to achieve the representative samples, while the Asphalt Institute model was used to obtain the dynamic modulus and fatigue life parameters for unmodified and modified conditions. Overall the research findings showed that CS improved the strain resistance, dynamic modulus (related to the stiffness of the HMA concrete), and fatigue performance of the asphalt concrete as forecasted because of the binding qualities of the CS. However, the optimum binder modification content to attain maximum values for both parameters was recorded at 5%. Thus, CS has the potential to be an excellent material for improving the strength performance characteristics of asphalt concrete pavements.*

Background*: Good road infrastructure is an essential component of a stable economy. Asphalt concrete is a popular mixture of asphalt or bitumen and aggregates widely used for road construction because of its effective binding properties. Asphalt concrete pavements are being subjected to increasing loads of diverse forms and stresses, and these cause the pavements' useful life to deteriorate considerably. In addition, greenhouse gases (GHG) in the atmosphere are becoming a more significant cause for concern due to the effects of climate change, and embodied carbon from asphalt production and construction is a direct contributor to these emissions, necessitating a reduction in the amount of asphalt used for road construction.*

The actions of modifying the asphalt paving materials started a long time ago, and hopes were initially sought in earlier experiments of incorporating natural rubber with asphalt in the 1840s to capture the flexible nature of rubber in a longer-lasting paving surface (Sulyman, 2014). Many studies have been conducted to ascertain the effect of different modifiers on asphalt pavement. Polymers are one of the most recommended materials for modifying asphalt concrete in flexible pavements because they have been investigated to significantly improve asphalt properties (Becker, Mendez & Yajaira, 2000). Research and practice have shown that using a polymer-modified asphalt binder can significantly improve the fatigue resistance of a Hot Mix Asphalt (HMA) mixture (Asphalt Institute Inc., 2014). Some reasons for utilizing these polymers include; improving the abrasion resistance of asphalt blends, obtaining softer blends at low temperatures and reducing cracking, increasing the strength and stability of the mixture and obtaining stiffer blends at a high temperature and reducing rutting (Lewandoski, 1994).

Today, Highway agencies have recognized the benefits of using modified asphalts to reduce the amount and severity of pavement distress and increase service life (Walker,2015). Modified asphalts are often referred to as "polymer-modified asphalts" because polymers are probably the most common type of modification. Modified asphalts may be produced in several ways, and we have some other categories of modifiers that are also essential in asphalt modification. These could be fillers such as crusher fines, fly ash, and carbon black; extenders such as sulfur and lignin; rubbers both natural or synthetic; plastics such as polyethylene, ethylene acrylate, copolymer, and polyvinyl chloride; fiber such as natural asbestos, rock wool, polyester, fiberglass and mineral; oxidants such as manganese salts; antistripping agents such as amines and lime, and various other waste materials (Roberts, 1996).

Different admixtures or modifiers have different effects on asphalt concrete. Various studies have shown that polymers are very effective modifiers as they are unique in allowing brittle and ductile materials to become softer and more substantial. At high temperatures and adequate mixing with asphalt, polymers incorporate asphalt molecules and then form a network that involves the entire binder and results in significant improvement of the viscoelastic properties in comparison with those of the base binder mix (Polacco, Filippi, Merusi&Stastna 2015). Polymers are added to asphalt blends to improve strength and reduce temperature susceptibility (Al, Yi-Qiu& Hameed, 2011). Modifying asphalt with various polymers, including

polyethylene polypropylene, has become paramount for improving high and low-temperature characteristics of asphalt compositions and their toughness and durability in the construction industry today. Many additives such as Styrene butadiene polymers, polyethylene-based polymers, polychloroprene-based polymers, gilsonite oils, and a lot of other modifiers, including tall oil, have been added to asphalt to improve various engineering properties for a better mix in construction (Al, Yi-Qiu& Hameed2011)

Recent research has proven that the most beneficial polymer modifiers that improve the asphalt concrete mix properties are relatively expensive, of recycled/ artificial origin, and produce significant embodied carbon. In light of this, there is a need to explore locally-sourced natural modifiers to modify asphalt concrete. Polymers exist in either natural or synthetic forms. They are any class of natural or synthetic substances composed of large molecules called macromolecules, which are branches of simpler chemical units called monomers (The Editors of Britannica Encyclopedia, 2020). Starch comprises glucose polymers (amylopectin & amylase) (Bull et al., 2018). Corn starch is a versatile material used in industries for adhesives, paper products, anti-sticking agents, and textile manufacturing. Its effects in asphalt concrete were explored because asphalt is necessary for flexible pavement wearing courses but is an expensive component and high carbon emitting material. Although it would be challenging to replace asphalt completely, we could achieve lesser CO2 emissions by partial replacements with alternative eco-friendly materials (CS in this case) for road construction.

Materials and Methods:*The Marshall Mix design procedure for designing HMA concrete was adopted for this research. The Marshall methodology incorporates a laboratory experiment to generate a suitable asphalt mixture by analyzing stability/flow, density/air voids, and void in mineral aggregate (VMA). Marshal Design Procedures for Asphalt Concrete Mixes, as presented by Asphalt Institute (1956), National Asphalt Pavement Association (1982), and Roberts et al., were used to prepare the samples (1996). The processes involved producing some test specimens for a variety of asphalt (bitumen) contents in order for test data curves to display well-defined values. The tests were prepared in 2.5 percent increments of asphalt. To give appropriate data, three replicate test specimens were generated for each level of asphalt content. Before adding the asphalt to the unmodified samples, the aggregates were heated for about 5 minutes to allow for absorption into the aggregates. The mixture was then placed into a mold and crushed with 75 blows on both faces 450mm using a 6.5kg-rammer 450m high. Compacted specimens were tested for bulk-specific gravity, stability and flow, density, and voids at 600 degrees Celsius, as prescribed by the AASHTO Design Guide (2002). The findings were utilized to determine the optimum asphalt content of unmodified concrete. The corn starch content was added to the asphalt binder in increments of 2.5 percent by weight (0 - 10 percent). The Marshall approach comprises a laboratory experiment to generate a suitable asphalt mixture by analyzing stability/flow, density/air voids, and void in mineral aggregate (VMA).*

Results*: The Dynamic Modulus and Fatigue Resistance properties of Corn-starch modified asphalt mixes performed better than the conventional (Unmodified) HMA concrete. Mix design properties such as stability, flow, density, air voids, and VMA obtained from Corn Starch modified asphalt concrete also performed better than conventional (Unmodified) HMA concrete.*

Conclusion:*In order to address the current climate crisis and improve pavement performance, research has been conducted on alternate materials for asphalt concrete improvement. This research has been influenced by the increased cost and difficulty of acquiring construction materials, the embodied carbon from manufacturing materials, and increased highway traffic loads.*
A review of the related literature reveals that although a great deal of research has been conducted on the use of alternative materials for improving pavement performance, a substantial amount of work remains because pavement performance is dependent on the prevailing conditions in different geographic regions and the majority of novel explored materials still leave a significant carbon footprint on the environment.
The conclusions of this study are based on the research's objective and general findings. The objective of this research was to determine the influence of CS on the performance of HMA concrete, and the acquired data could help identify this effect. Consequently, the following conclusions can be drawn; the elastic parameters such as Dynamic Modulus (E) and Fatigue resistance properties of the modified HMA concrete were improved with the addition of Corn Starch. However, 5% CS content by weight of the binder is the threshold content to attain optimum Marshall values, dynamic modulus, and fatigue life for Heavy traffic conditions.*
Key Word*: Corn Starch; Hot Mix Asphalt; Dynamic Modulus; Binder Modifier; Marshal Stability; Fatigue.*

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I.Introduction

The components of asphaltic mixtures are aggregates and bituminous cement. The bituminous cement (mastic) is composed of bitumen, sand, and fine filler particles, and it may contain additives such as polymers, phosphoric acid, or hydrated lime. The term "embodied carbon" refers to the greenhouse gas emissions produced during a material's production, shipping, installation, and disposal, which contributes significantly to global warming measured as a factor (KgCO2e). Asphaltic pavements are relatively expensive to construct due to the cost of the asphalt binder, which accounts for a significant amount of embodied carbon emissions. Recent research has been tailored to the use of naturally occurring polymers such as; rubber latex & cellulose, which have been proven to be very useful in enhancing the quality of asphalt concrete pavement wearing course; however, they are expensive and not readily available (Abbas & Abbas 2016: Al-Sabaeeia, Yussofb, Napiaha, &Sutanto, 2019). Corn starch, a natural polymer with a similar chemical structure to cellulose, is cheap, of low carbon factor, and readily available in Nigeria; it can be put to work to see its contribution in enhancing the strength and fatigue resistance of asphalt concrete pavements

II.Material and Methods

The materials used in this research will include fine and coarse aggregates, bitumen, and corn starch (CS). The corn starch was obtained by soaking at room temperature corn grains purchased from mile III market, Port Harcourt, Rivers State, Nigeria, for 48 hours and then draining and sun-drying them to extract all traces of moisture. The coarse aggregate used was all-in graded gravel having a maximum size of approximately half-inch (12.7mm) and was obtained from the local building materials market at Mile III, Diobu Port Harcourt, Rivers State, Nigeria. The asphalt cement or bitumen was 60/70 penetration grade and was obtained from the materials laboratory of the Civil Engineering Department of Rivers State University, Port Harcourt, Rivers State, Nigeria. The fine aggregate utilized was sharp sand with a maximum particle size of 4.75mm bought from a local distributor at the Mile III, Diobu, Port Harcourt, Rivers State, Nigeria Building Materials market.
After collecting samples of the materials, laboratory tests were conducted, including specific gravity, asphalt grading, and sieve analysis of the aggregates used for mix proportioning by the straight-line method.

Study Design: Experimental research
Study Location: Civil Engineering Department, Materials Laboratory, Rivers State University, NkpoluOroworukwo, Port Harcourt, Rivers State, Nigeria.
Study Duration: October 2020 to April 2021.
Sample size: 27 briquettes**.**
Calculation of sample size: The sample size was estimated using modified and unmodified samples. The total number of samples for each test, modified and unmodified, was 27; two distinct batches were generated.
The first 15 samples were utilized to prepare for the preliminary stability, flow, density, air void, and VMA and RMS testing. The strain, dynamic modulus, and fatigue life were calculated using the second 12 samples.

Collection of Data: The process for data collection includes testing materials to determine their physical properties. It entails conducting particle size distribution (grading assessment) for coarse and fine aggregates. In addition, an aggregate combination based on the straight-line method was used to gather the essential results and data for analysis. Preparing the sample allowed for further examination to get bulk-specific gravity, stability, flow, density, and voids, which were then utilized in the pavement study.

Materials Used
The following materials were used during this research work;
- ❖ Bitumen (Penetration grade 60/70)
- ❖ Coarse aggregate (Granite)
- ❖ Fine aggregate (White river sharp sand)
- ❖ Corn Starch (Binder replacement material)

Methods
- Sampling of the materials
- Laboratory tests/experiments
- Analysis of the results obtained

Laboratory Experiments and Tests
This research's laboratory tests and experiments involve classifying materials utilized for sample preparation, blending aggregates, and creating specimens typical of the asphalt concrete pavement under inquiry.

Material Classification
In order to classify the materials employed in this study, physical property tests were conducted. These tests involve determining the specific gravity of the modifier, coarse and fine particles, and bitumen. In addition, penetration, viscosity, and softening point tests were conducted on the bitumen.

(a) Bituminous Cement
As a binder, bituminous cement was subjected to the following four physical property tests:

-Specific Gravity
The pycnometer method was used to determine the weight of a specific volume of binder (asphalt cement) and the weight of an equivalent volume of water.
The specific gravity was determined by dividing the volume of the binder by the weight of an equal volume of water
-Bitumen Penetration tests
The penetration test measured the depth to which a standard needle entered a well-prepared sample of bituminous cement under precisely specified temperature, stress, and time conditions. Utilizing a Penetrometer that allowed a 100-gram needle to go vertically downward without friction, the penetration of the bitumen was measured as the distance travelled by the needle in units of tenths of millimetres. However, the technique was done four times, and the average penetration value was acquired for further investigation.

-The viscosity of Bituminous Cement
The bituminous cement's viscosity was evaluated using a Say-Bolt Furol viscometer to determine the asphalt cement's resistance to flow. The test monitored the time required for 50 ml of the binder to pass through a given aperture at a predetermined temperature.
-Softening Point of Bituminous Cement
For the softening point test, a steel ball was placed atop a mass of asphalt cement encased in a brass ring and heated in a water bath until the ball fell through the bituminous cement. The temperature at which the ball fell was recorded as the bitumen's softening point.

Table 2.1: Physical properties of Bituminous Cement

TEST	SPECIFIC GRAVITY (g)	GRADE OF BINDER	PENETRATION (mm)	VISCOSITY (Secs)	SOFTENING POINT (^{0}C)
RESULTS	1.030	60/70	51 ℃, 100bgm, 0.1mm	68.6	50 ℃
SYMBOL	Gs	G	Pe	V (60 ℃)	SP
ASTM DESIGNATION NO.	D-70	D-5			D-36

(b) Aggregates
The aggregates utilized during this research project went through the following tests:
Specific Gravity
The coarse and fine aggregates were subjected to the specific gravity tests, and the results recorded. However, the test procedure required 24 hours of soaking a specific weight of aggregates in distilled water before weighing them in water. The sample was then surface-dried and weighed in air, followed by 24 hours of oven-drying at 1050°C and weighing in air. Consequently, the specific gravities of the samples were calculated by dividing the weight of the oven-dried samples in the air by the weight loss of the saturated sample in water.

Table 2.2: Physical properties of Coarse and Fine aggregates

AGGREGATE	COARSE	FINE	Test method
Bulk specific gravity	2.73	2.70	ASTM C - 127

Aggregate Gradation Analysis

Aggregate gradations for coarse and fine aggregates were performed, and the findings were documented using graphical plots to show the particle size distribution. The laboratory approach entailed weighing both aggregates and shaking them for less than two minutes on each sieve size. The percentage retained on each sieve size was calculated. Similarly, the cumulative percent passing on each sieve was determined by subtracting the cumulative percent kept on each sieve from 100% of each sieve size. Furthermore, the particle size distributions were calculated by dividing the cumulative percent passing on each sieve size by the corresponding sieve size. In addition, the sieve analysis results are shown in Tables 2.3 and 2.4

Table 2.3 Gradation of Coarse Aggregate (Sample Size = 1200g)

Sieve No. (mm)	Mass Retained	Cumulative mass retained	Percentage Retained	Percentage Passing
19.0	0	0	0	100
12.5	79.1	79.1	6.59	93.41
9.5	564.9	644	53.67	46.33
6.3	440.1	1084.1	90.34	9.66
4.75	85.8	1169.9	97.49	2.51
2.36	16.5	1186.4	98.87	1.13
1.18	0	1186.4	98.87	1.13
0.6	0	11864.4	98.87	1.13
0.3	1.5	1187.9	98.99	1.01
0.15	2.3	1190.2	99.18	0.82
0.075	5.0	1195.2	99.6	0.4
PAN	4.1	1199.3	99.94	0.06

Table 2.4 Gradation of Sand (Sample Size = 500g)

Sieve No. (mm)	Mass Retained	Cumulative mass retained	Percentage Retained	Percentage Passing
19.0	0	0	0	100
12.5	0	0	0	100
9.5	5.0	5.0	1	99
6.3	6.5	11.5	2.3	97.7
4.75	13.0	24.5	4.9	95.1
2.36	41.2	65.7	13.14	86.86
1.18	62.8	128.5	25.7	74.3
0.6	63.8	192.3	38.46	61.54
0.3	211.7	404	80.8	19.2
0.15	65.6	469.6	93.92	6.08
0.075	24.8	494.4	98.88	1.12
PAN	3.7	498.1	99.61	0.38

Table 2.5Schedule of Mix proportion for Aggregates

Sieve size (mm)	Specification Limit	(%) of passing Aggregate A	(%) of passing Aggregate B	Mix proportion 0.532A+0.4675B
19.0	100	100	100	100
12.5	86-100	93.41	100	96.49
9.5	70-90	46.33	99	70.95
6.3	45-70	9.66	97.7	50.82
4.75	40-60	2.51	93.1	44.86

2.36	30-52	1.13	86.86	41.21
1.18	22-40	1.13	74.3	35.34
0.6	16-30	1.13	61.54	29.37
0.3	9-19	1.01	19.20	9.51
0.15	3-7	0.82	6.08	3.28
0.075	0	0.40	1.12	0.74
PAN	0	0.06	0.38	

(c) MODIFIER
The modifier used for this research was corn starch, and the specific gravity test was carried out on the sample

Specific Gravity of Modifier(Corn Starch)
The modifier's weight was determined using the pycnometer method, which was also used to determine the weight of an equivalent volume of water. Thus, the weight of an equal volume of the modifier was divided by the weight of an equal volume of water to determine the specific gravity. Table 2.6 below displays the outcome of the modifier's specific gravity.

Table 2.6: Specific Gravity Test Results of Modifier (Corn Starch)

TEST	SPECIFIC GRAVITY
RESULT (g)	1.51

Dynamic Modulus (*E)
The dynamic modulus of an asphalt mixture is an important characteristic that determines the material's capacity to resist compressive deformation under cyclic compressive loading and unloading (Rowe, Hakimzadeh, and Blankenship, 2008). Because of its considerable link with critical pavement distresses, such as rutting and fatigue cracking, the dynamic modulus is an essential critical input parameter (Witczak, Pellinen, and El-Basyouny, 2002). As a result, it is used to forecast the performance of asphalt pavements. The Asphalt Institute devised a design approach in which the dynamic modulus is calculated using the equations presented in Huang's (1993), as shown below.

$E^* = 100{,}000\ (10^{\beta_1})$

$$\beta_1 = \beta_3 + 0.000005\beta_2 - 0.00189\beta_2 f^{-1.1}$$

$$\beta_2 = \beta_4{}^{0.5} T^{\beta_5}$$

$$\beta_3 = 0.553833 + 0.028829\left(P_{200} f^{-0.1703}\right) - 0.03476V_a + 0.07037\lambda + 0.931757 f^{-0.02774} \quad \beta_4 = 0.483V_b$$

$$\beta_5 = 1.3 + 0.49825\log f$$

$\lambda = 29{,}508.2\ (P_{77°F})^{-2.1939}$

Where;
E^* = dynamic modulus (psi)
f =loading frequency (1Hz, 5Hz and 10Hz)
T = temperature (°F) (Mixing Temperature)
V_a = volume of air voids (%)
λ = asphalt viscosity at 77°F (10^6 poises)
P_{200} = percentage by weight of aggregates passing No. 200 (%)
V_b = volume of bitumen (m^3)
$P_{77°F}$= penetration at 77°F or 25°C
S_i= maximum stability in the times series condition set based on i.e. (1-14 days) S_o=maximum stability in unconditioned set (0 days)

Fatigue Life

Fatigue is the distress in the road pavement due to repeated cyclic loading or tire pressures. A pavement will accommodate the total number of design load repetitions within the design and serviceability years (Igwe, 2019). The asphalt institute (Asphalt Institute, 1982) suggested that the relationship between fatigue cracking and tensile strain is represented by the number of load repetitions as follows;

$N_f = S_f * 10^{[4.84(VFA-0.69)]} * 0.004325 * E_t^{-3.291} * E^{-0.845}$

where;

E = dynamic modulus

VFA = voids in aggregate filled with asphalt (%)

$$VFA = 100 * \left(\frac{VMA - Va}{VMA}\right)$$

VMA = voids in mineral aggregate (%)

V_a = air voids (%)

S_f = shift factor to convert laboratory test results to field

However, to curb the effects of shift factors S_f, the Asphalt Institute model was further modified to accommodate shift factors from various combinations of asphalt binder types and grades (Asphalt Institute, 1999). The resulting equation is of the form which shall be adopted in this work;

$$N_f = 0.0796(\varepsilon_t)^{-3.291}(E)^{-0.845}$$

where;

N_f = number of load repetitions to failure

E = dynamic modulus

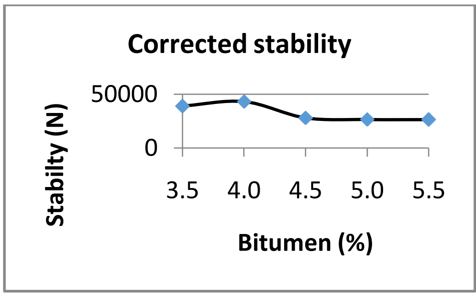
ε_t = tensile strain at the bottom of the asphalt bound layer

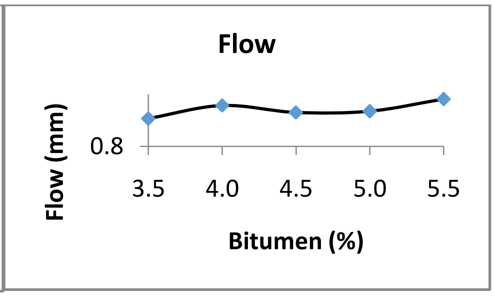
III.Result

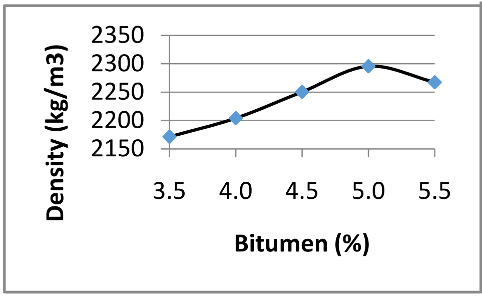
Below is a presentation of the unmodified and the Corn Starch (CS) modified asphalt concrete sample results, evaluating their performances. For ease of illustration, the laboratory experiment findings were given in the categories of the various tests. These categories include the results obtained for the Marshal Properties, Dynamic Modulus, and Fatigue resistance that were considered for this research concerning the increase in the modifier content (corn starch) from 2-10 percent at 2.5 percent increments, for a heavy traffic volumes, in accordance with the objectives of this research.

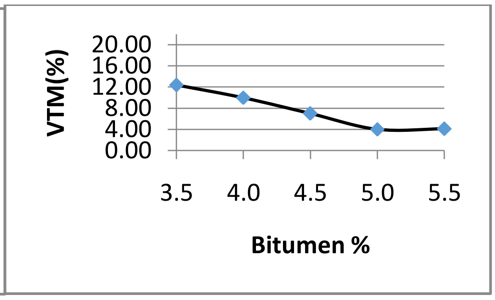
3.1: Summary of Mix Design Properties for Unmodified Asphaltic Concrete

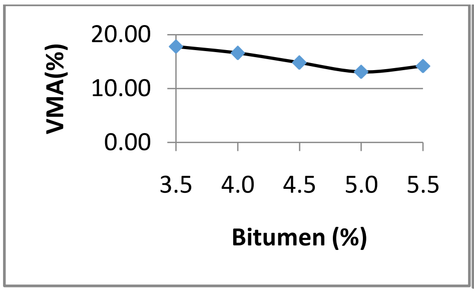
Bitumen %	Gmb	Density(kg/m3)	Stability	Flow(mm)	VTM(%)	VMA(%)	VFA(%)
3.5	2.171	2171.3	40100	1.01	12.38	17.80	30.48
4.0	2.204	2203.8	40500	1.09	10.00	16.57	39.69
4.5	2.250	2250.3	34450	1.16	7.00	14.81	52.73
5.0	2.295	2295.5	42200	1.19	4.02	13.10	69.30
5.5	2.267	2267.4	29950	1.26	4.10	14.17	71.09

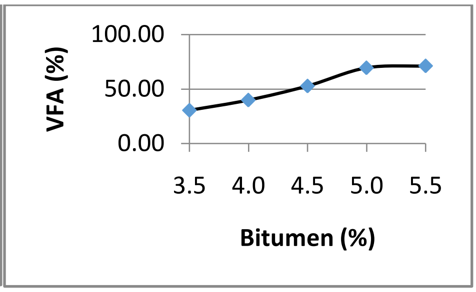






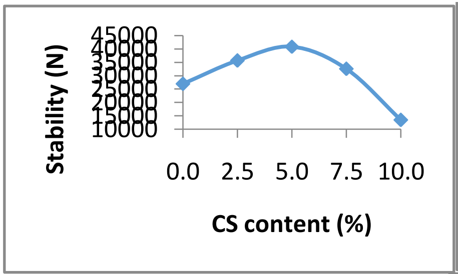


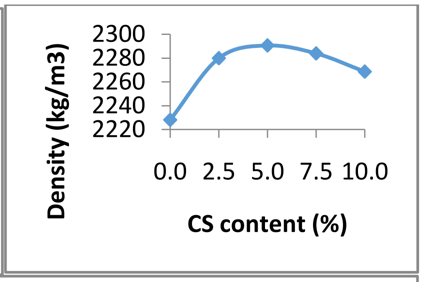


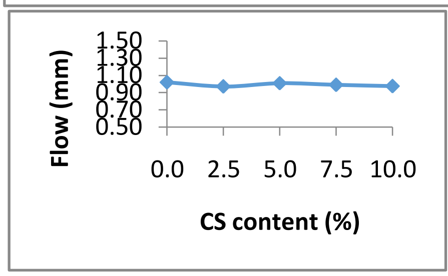


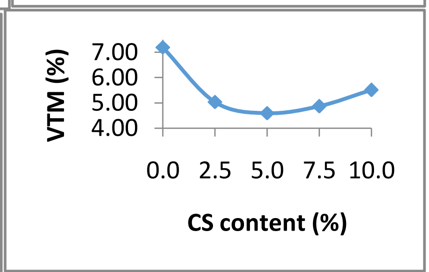
3.2: Summary of Mix Properties for Unmodified Asphalt Concrete

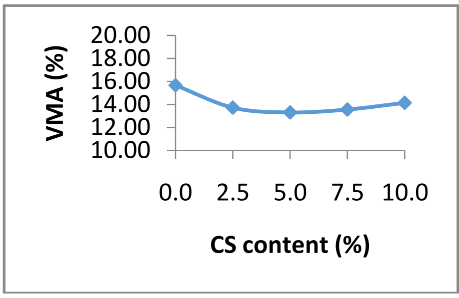
CS %	Gmb	Density(kg/m3)	Stability	Flow(mm)	VTM(%)	VMA(%)	VFA(%)
o	2.228	2228	26950	0.98	7.19	15.66	54.06
2.5	2.280	2280	31250	1.01	5.04	13.70	63.23
5.0	2.290	2290	35800	0.98	4.59	13.29	65.45
7.5	2.284	2284	27350	1.01	4.87	13.54	64.06
10.0	2.268	2268	11850	0.96	5.51	14.13	61.00

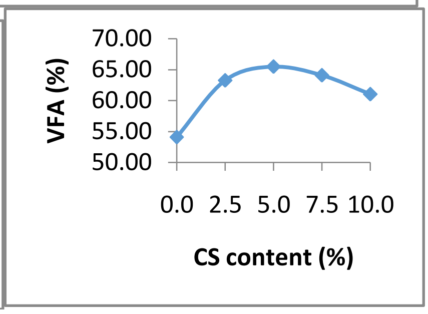












3.3: Summary of Mix Properties for Unmodified Asphalt Concrete

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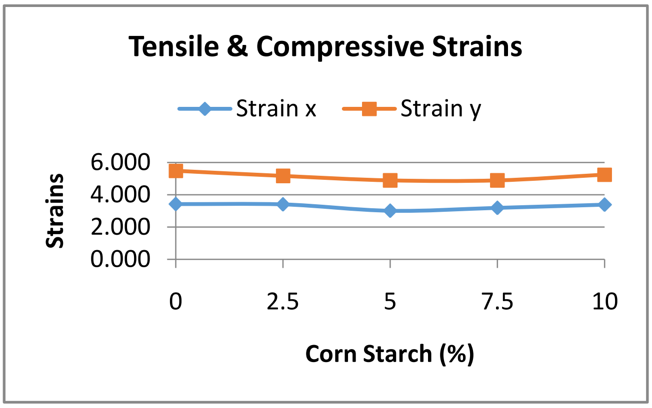
10.0	2.268	2268	11850	0.96	5.51	14.13	61.00

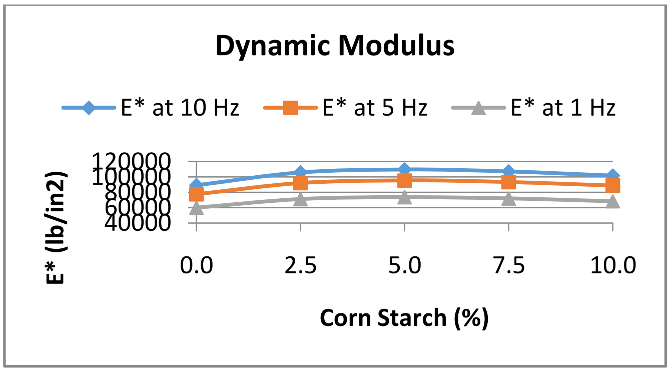
3. 4Variation of Tensile and Compressive Strains of Modified Asphalt Concrete at varying CS content

CS %	ε_x (10^{-5})	ε_y (10^{-5})
0	3.43	5.50
2.5	3.41	5.18
5	3.01	4.90
7.5	3.19	4.90
10	3.39	5.26



3.5Variation of Dynamic Modulus of Modified Asphalt Concrete at varying CS content

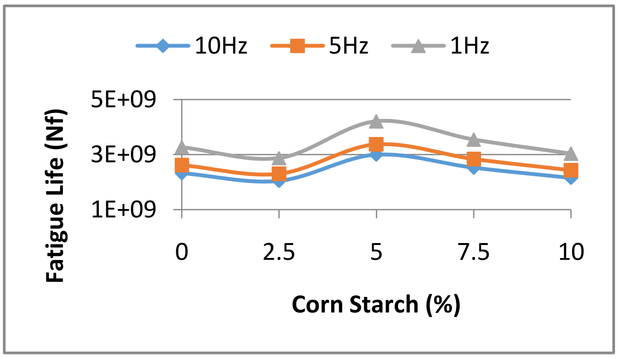
CS %	E* at 10 Hz	E* at 5 Hz	E* at 1 Hz
0	89087	77594	59793
2.5	105866	92208	71055
5	109696	95544	73625
7.5	107316	93471	72028
10	101933	88783	68415



3.6Variation of Fatigue Life (N_f of Modified Asphalt Concrete at varying CS content

CS %	Nf at 10 Hz	Nf at 5 Hz	Nf at 1 Hz
0	2328733915	2620280425	3273403976
2.5	2048694539	2305181439	2879764324
5	2996604148	3371764863	4212201259

7.5	2522030163	2837776452	3545112435
10	2157375231	2427468441	3032532232



IV. Discussion

The behavior of the strains, dynamic modulus, and fatigue lifeparametersfor the modified and unmodified samples as represented in the illustrations above will be discussed in this section.

The Tensile (ε_x) and Compressive (ε_y) Strains of the CS-modified mixes declined linearly with increasing CS content. Compared to the unmodified mix, Tensile Strain $\varepsilon_x$varied by 1%upon the addition of 2.5% CS. At 5% CS content, $\varepsilon_y$decreased by 12%; $\varepsilon_y$also decreased by 7% at 7.5% CS content and by 1% upon addition of 10% CS. Similarly, $\varepsilon_x$varied by 6%upon the addition of 2.5% CS. At 5% CS content, ε_x decreased by 11%; ε_x also decreased by 11% at 7.5% CS content and by 4% upon addition of 10% CS. The Tensile and compressive strains show the rate at which the surfaceof the modified mixes will perform against rolling loads. These parameters represent how well the HMA will resist rolling loads throughout its service life. However, it is worth noting that although the tensile and compressive strains begin to increase beyond 5% CS content, the results show better performance than the unmodified mix. Therefore, while the unmodified mix has given a threshold fatigue performance against loading to strains and deformation, it is clear that CS significantly improves the strain performance of the mix and establishes 5% by weight of the asphalt to achieve the best results

Dynamic Modulus (E*) at various load frequencies (1Hz, 5Hz and 10Hz) increased linearly with increasing CS content. Table 3.2 shows that compared with the control mix, the dynamic modulus E* at a frequency of 1Hz increased by 19% from 59793 PSI for the unmodified mix to 71055 PSI upon the addition of 2.5% CS. Dynamic modulus further increased by 23% to 73625 PSI at 5% CS content, 20% to 72028 PSI at 7.5% CS content, and 14% to 68415 PSI at 10% CS content, respectively. Similarly, at a frequency of 5Hz, the dynamic modulus increased by 19% from 77594 PSI for the unmodified mix to 92208 PSI upon adding 2.5% CS. Dynamic modulus further increased by 23% to 95544 PSI at 5% CS content; increased by 20% to 93471 PSI at 7.5% CS content; increased by 14% to 88783 PSI at 10% CS content, respectively.At 10Hz frequency, the dynamic modulus follows the same trend as the previous, increasing by 19% from 89087 PSI for the unmodified mix to 105866 PSI after adding 2.5% CS. Dynamic modulus further increased by 23% to 109696 PSI at 5% CS content, 20% to 107316 PSI at 7.5% CS content, and 14% to 101933 PSI at 10% CS content, respectively. This indicates that an increase in CS content caused a corresponding increase in the stiffness of the modified asphalt concrete mix. This increasing stiffness may result from the increase in bulk density of the mix resulting from the addition of the CS material. Starch has been known to possess gelatinization properties due to larger size granules (i.e. as compared to the size of amylose/amylopectin mixtures), which have become soluble in the hot mixture, thus increasing its viscosity which contributes to its cementitious properties. Similar research on the effect of starch on HMA shows that these properties may be responsible for the increase in bulk density of the HMA, which translates to increased strength and stiffness (Al-Hadidy, Tan & Ayman, 2010).l

The fatigue life (Nf) behavior of the CS-modified mix is shown in fig 3.3. At a frequency of 1 Hz, Nf varied from 3273403976 for the unmodified mix to 28793403976 upon addition of 2.5% CS; 4212201259 at 5%; 3545112435 at 7.5%; and 3032532232 at 10% CS. Similarly, at 5Hz frequency, Nf varied from 2620280425 for the unmodified mix to 2305181439 upon addition of 2.5% CS; 3371764863 at 5%; 2837776452 at 7.5%; and 2427468441 at 10% CS content. Furthermore, at 10Hz frequency, load repetitions to failure varied from 2328733915 for the unmodified mix to 2048694539 upon addition of 2.5% CS; 2996604148 at 5%; 2522030163 at 7.5%; and 2157375231 at 10% CS content. The results obtained for load repetitions to failure (i.e. fatigue life) of the various mixes indicate a close relationship between the stiffness modulus and fatigue life across the various CS content. Load repetitions to failure of asphalt concrete mixes found in the literature are believed to depend on specific conditions. However, from the results of Fatigue life (Nf) conducted for this study, it was found that the values increased with increasing CS content for the various load frequencies. Although figure 3.3 shows that Fatigue life tends to decrease as the loading frequency increases.

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