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Mechanical properties of cold mixed asphalt

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ABSTRACT

The mechanical and performance characteristics of cold mix asphalt derived from straight-run bitumen blended with dissolved polythene were assessed to determine the engineering, environmental, and economic feasibility of a recently developed product for pavement maintenance. The cold mix asphalt binder was created by treating a portion of straight-run bitumen with chemically dissolved polythene waste sachets at a temperature of approximately 80°C, employing an alkaline emulsifier, chemical surfactant, and water. The formulation for the cold mix asphalt involved 35% coarse aggregates, 65% fine aggregate, and 10% mineral filler, with an optimal binder content of 8.3%. Standard laboratory Marshall tests, static loading/unloading in both laboratory and field settings, and real-time traffic loads were applied to the cold asphalt mixes to establish comparative performance. The Marshall Stability, flow, and density of the experimental cold mix asphalt were determined as 5.08 kN, 4.0 mm, and 1.98 g/cm3, respectively. In comparison, the corresponding values for the other three commercially available cold asphalt mixes ranged from 0 to 4.27 kN, 0 to 5.5 mm, and 1.60 to 1.85 g/cm3. The rate of deformation of experimental cold mix with respect to time and traffic load respectively 0.0086mm/week and 0.00877mm/standard 80 kN standard axle, which are more favorable than the corresponding values for the commercial mixes.

KEYWORDS

Bitumen, Cold asphalt, Cold bitumen, Pavement, Polythene

1. INTRODUCTION

According to Yoder and Witczaks [1] pavement refers to the material that forms the layer of a road structure, situated above the natural soil. The primary purpose of pavement is to ensure that the pressure exerted by wheel loads does not surpass the supporting capacity of the foundation, beneath it known as the subgrade. This pavement is of two main types, flexible (Asphalt), transmitting load through grain-to-grain contact and rigid (Concrete), which transmits its load through flexural strength of the concrete [2].

Bitumen is extensively employed as a construction material in civil engineering; however, its mechanical properties present greater complexity compared to conventional civil engineering materials like steel, cement, or concrete (BS 3690, BSI, 1989a). It is a non-crystalline, viscous substance with a black or dark brown appearance, substantially soluble in carbon disulphide (CS2), and characterized by adhesive and waterproofing qualities. Comprising predominantly of hydrocarbons, bitumen typically contains a minimum of 80% carbon and 15% hydrogen, with the remaining composition including oxygen, sulphur, nitrogen, and traces of various metals [3]. It is usually obtained through a distillation process.

As of the close of the 20th century, global bitumen emulsion production was estimated to surpass 7 million tonnes [4]. Table 2.3 indicates that the United States is the primary producer, with France being the leading consumer of bitumen emulsions. Currently, approximately 5-10% of the world's paving-grade bitumen is allocated for emulsions, and the United States continues to hold the position of the world's largest emulsion producer [5]. There are various types of asphalt mixes; but which can be categorized into three major groups, Natural asphalt, Hot-Mix asphalt and more recently cold mix asphalt [6].

Hot mix asphalt is a blend of mineral aggregates and binder, typically bitumen, in precise proportions. The traditional method of asphalt production involves the application of heat at around 160°C to 180°C using advanced equipment [7]. This elevated temperature is crucial for reducing viscosity and eliminating moisture during the manufacturing process, ultimately resulting in a durable material. Hot mix asphalt (HMA) is commonly employed in high-traffic areas such as busy highways and airports. On the other hand, cold mix asphalt (CMA), the primary focus of this study, can be produced at room temperature and is suitable for intercity and low-traffic road pavements. This alternative to HMA offers versatility in application. However, HMA is associated with several drawbacks, including: (i) High costs related to plant procurement, maintenance, and running time. (ii) The need for skilled personnel to ensure proper asphalt mix production, laying, and compaction. (iii) The inability to store the material, as it must be used promptly in its hot state. (iv) Limited haulage distance due to the stiffening effect of wind and air on the material. (v) Elevated safety risks for workers during the production and laying process, involving factors such as high temperatures and the release of hazardous gases into the air.

Cold asphalt, also known as bitumen emulsion, is composed of cold bitumen. This emulsion consists of three components: bitumen, water, and an emulsifying agent. It forms a two-phase system with two immiscible liquids. The bitumen is dispersed in the continuous aqueous phase as discrete globules, typically ranging from 0.1 to 50 μm in diameter. Electrostatic charges, stabilized by an emulsifier, keep the bitumen in suspension. Emulsifiers contain polar (hydrophilic) and non-polar (hydrophobic) groups. This unique arrangement allows the emulsifier to position itself among the hydrophobic bitumen-soluble group and the hydrophilic water-soluble group. The emulsifier plays crucial roles in the bitumen emulsion system, as identified by Gorman et al. [8]: (i) mitigating the interfacial tension between bitumen and water, and (ii) facilitating the formation of an emulsion to stabilize it, providing long and short-range stabilizing forces when cooled. Furthermore, insights from Gaughan [9] and Remtulla & Swanston [10] emphasized that Cold Mix Asphalt (CMA) offers distinct advantages over Hot Mix Asphalt (HMA) beyond load-bearing capacity and immediate usage [11]. (i) Storage Capability: Exhibits the capacity for storage for up to 12 months. (ii) Transportability: Can be efficiently transported to any global location upon request. (iii) Requires minimal complexity and compatibility in both labor (personnel) and machinery for cold mix pavement. (iv) Demonstrates insensitivity to climatic conditions and road temperature during application. (v) Cold asphalt application is more time-efficient compared to hot mix asphalt. (vi) Applied at lower temperatures, cold mix asphalt utilizes water as a medium, resulting in a more cost-effective and safer application than hot mix asphalt, which demands a working temperature of not less than 120°C for pavement work. (vii) Cold asphalt can be easily cleansed from equipment using water, while the cleaning process for hot mix asphalt equipment typically involves lighter petroleum products. (viii) The cold asphalt product is environmentally friendly, as the production process and laying phase eliminate hazardous gases. (ix) Adhesive properties can be enhanced through the addition of processed rubber and other fibers/modifiers in the mix [12].

Modification of bitumen with other additives to improve the main service performance characteristics of durability, resistance to ageing, elasticity and/or plasticity that have other concomitant benefits i.e., environmental cleanliness, risk elimination etc. is worth being examined as probable reduction of attended risk of pavement repairs with HMA. Achieving the modification with a non-degradable environmental waste shall be an added ad-vantage for a developing economy. Such material as natural rubbers, polymers (which include styrene butadiene styrene (SBS), thermoplastic rubbers and ethylene vinyl acetate (EVA) are commonly used to modify bitumen. The modifier, the polythene water packaging wastes, a family of polymers with the desirable properties of flexibility or viscosity, higher heat resistant, higher strength against aging, which make it a good candidate for modification of bitumen and the material of choice for this study has also been identified by Kolo and Jimoh [13] and Alan and Akzo [14], to have positive impacts of modification when processed with bi-tumen. The impacts include (i) savings in the cost of pavement works with partial and or complete substitution of bitumen (ii) conservation of foreign reserve (iii) environmental pollution control, amongst others. Mechanistic – Empirical (M-E) Design of flexible pavements desires the knowledge of mechanical proper-ties such as the elastic properties of each of the layers as well as stiffness and rheological properties of the bitumen bounded top layers of concrete [15]. The modification to the binder obviously has im-plication on the prevailing values of the mechanical properties normally desirable for the M-E design and performance monitoring of the mixes during service. Hence there is the need to have comprehensive information on the physical and mechanical (strength) properties of cold mix asphalt before adoption as a preferred maintenance material in tropical/ sub-tropical region [16]. Presented in this work is the production and modification of cold asphalt and its comparison to other three (3) types of cold asphalt, as well as their properties and durability with dissolved pure water sachets waste (DPWS-polythene) with the following benefit [11]:

I. Strength enhancement: The used waste polythene water sachet was discovered to have positive effects on the produced cold asphalt.
II. Economic: The waste polythene water sachet can now be collected by unemployed persons for recycle in asphalt making factory
III. Environment: The polythene collected from the environment will free the environment of rubbish polythene waste, thereby leaving us with clean and healthy environment.
IV. Settlement estimations: Before now it's a difficult task to estimate what will be the settlement rate of an asphaltic pavement, but now it can be seen that the estimation of pavement settlement can be done with application of this research work.
V. Elasticity of asphalt: It has also been confirmed that asphalt elasticity can be confirm from the use of Teszagy's theory, this was also established using pundit apparatus.

2. Methodology

2.1. Materials

In the research work four (4) different types of cold asphalts were used one (1) was formulated in the Laboratory other were obtained from their various manufacturer and were subjected to various laboratory test to ascertain their properties and durability [17,18,19].

Table 1 presents a range of cold asphalt materials, providing details on their sources, physical properties, and compositions. Concise information, including identification/designation marks, is included in the table for clarity and reference.

Table 1: Cold mix asphalts used for the study

S/No	Sample	Description/Characteristic	Sources	Designation
1.	DPWS - Modified Bitumen cold asphalt	Black in colour. A mixture of aggregates and binder	Study/Experimental cold mixes	SDPWS
2.	Carboncor cold-mix asphalt	Black in colour. A mixture of aggregates, carbon shale and binder	Carboncor Nigeria, Sauka Kahuta, Niger State, Nigeria	Scarb
3.	Portland Emcor Cold-mix Asphalt	Black in colour. A mixture of aggregates and binder	Portland Paints and Products, Lagos, Nigeria.	Sportland
4.	UPM Cold-mix asphalt	Black in colour. A mixture of aggregates and binder	UPM Company, Uyo, Akwa Ibom State, Nigeria	Supm

2.2. Production process of polythene waste sachet (PWS) emulsion and blending with straight-run bitumen

In the production of cold bitumen, 60% of the modified straight-run bitumen which contain 20% of waste polythene water sachets and 80% of straight-run bitumen [13], was heated inside a cylindrical container to a temperature of 140°C to set all the carbon-carbon bond in to resonance and at this temperature the prepared constituent, which include 1% chemicals (NaOH), 7% emulsifier and 32% of water, was pre-heated to temperature of 90°C and allowed to flow together into another bigger container equipped with stationary rotor for proper mixing/blending of the bitumen and the other constituent of the emulsion. It was left to attain the prevalent temperature of the environment [20, 21, 22].

2.3. Production and laboratory testing of cold mix asphalt

The research involved the following stages:

I. Characterization of mix aggregates (coarse, fines, and fillers) to meet the specified Marshall and General specifications for pavement wearing courses on heavily trafficked roadways, as outlined by [23].

II. Preparation of the cold mix asphalt using dissolved pure water sachet (DPWS), referred to as Polythene modified cold asphalt or simply experimental cold asphalt.

III. Testing the properties of the polythene modified cold mix asphalt and comparing the obtained results with other available cold mix asphalts used in Nigeria.

2.4. Evaluation of appropriateness of dissolved polythene modified cold mix asphalt and other commercially available cold asphalt in used in Nigeria

This aspect includes laboratory and field performance evaluations. The evaluations involved laboratory and field settlement determinations as well as the setting rate of the Polythene modified cold asphalt and other commercial cold mix asphalt sourced in Nigeria. The specific stages of evaluation are as enumerated below: -

a. Dynamic Laboratory test
b. Elastic Properties test using PUNDIT apparatus and
c. Field Evaluation/settlement.

2.4.1. Dynamic laboratory testing of cold mix specimen

The settlement response of the cold mix asphalt to dynamic testing was observed in the laboratory using an enhanced testing rig illustrated in Figure 1.

Figure 1: Consolidation Process of Asphalt

Figure 2: Rheological Test of Asphalt in progress using PUNDIT Apparatus

The rig comprises a loading column with a vertical settlement (deformation) scale, indicated by a dial gauge. The dynamic loading method employed is detailed in Table 2 [24].

Table 2: Dynamic test procedure for cold sampled asphalts

Time	Time (hrs)	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9
15 s	0.0042	Place 75N load on the sample	Add another 75N, making loading on second day to be 150N	Unload 75N, making loading on third day to be 75N	Return the 75N, making loading on fourth day to be 150N	Add 150N, making loading on fifth day to be 300N	Add another 300N, making loading on day six to be 600N	Unload 300N, making loading on day 7 to be 300N	Return the 300N, making loading on day 8 to be 600N	Add 150N, making loading on day 9 to be 750N
30 s	0.0083									
1min	0.0167									
2 min	0.0333									
4 min	0.0067									
8 min	0.1333									
15 min	0.25									
30 min	0.5									
1 hr	1									
2 hrs	2									
4 hrs	4									
8 hrs	8									
12 hrs	12									
24 hrs	24									

Elastic properties with PUNDIT apparatus

Dynamic Elastic modulus (Ed) was determined for each of the materials using the NDT PUNDIT apparatus (see Figure 2) which measured the velocity of transverse waves with equation 1 [25].

$$E_d = \frac{\rho v^2 (1+\sigma)(1-2\sigma)}{1-\sigma} \quad (1)$$

Where ρ = density, v = velocity, σ = Poisson's ratio

2.4.2. Field evaluation/settlement

The field study of the cold asphalt was done by sealing some identified pot-holes with the different cold mix, to determine the behavior of the various cold mix asphalts (see Table 3), when subjected to repeated traffic loading and external weather conditions. Four months of intensive monitoring and traffic count of the repaired pothole was systematically conducted. Levelling instrument and Pundit rebound hammer was used to determine both settlement and hardness of the cold asphalt dynamic.

Figure 3: Rebound hammer test

3. RESULTS AND DISCUSSION

3.1. The modified bitumen properties

Presented in Table 3 is the modified cold bitumen and available standard for cold bitumen and was found to be in agreements with transport research [26]. The modified cold bitumen can be stored for hours before use, it has 100 % solubility in trichloroethylene, it has a very high flash point of 300°C, and it does not coagulate when left unused.

Table 3: Properties of DPWS modified cold bitumen

S/No	Properties of Cold Bitumen	Obtained Values for Modified Cold Bitumen	Specifications for Cold Bitumen
1.	Penetration at 25°C	80	80 – 150
2.	Coagulation of emulsion at low temperature	Nil	Nil
3.	Flash Point (°C)	300	220
4.	Solubility (%)	100	99

3.2. The aggregates properties

The used aggregates meet all the required properties of crushed aggregates and it was adjudged suitable for road surface construction material as presented in Table 4, which is in accordance to BS 812. Aggregates exhibiting impact value of less than 10 % are considered to be very strong. Aggregates within 10 % – 20 % are considered strong and 20 % - 30 % are suitable for surfacing in road construction and for base coarse aggregates impact value should not exceed 45 % and for wearing course 30 % is adequate.

Table 4: The aggregates indices properties

Cold Asphalt	Aggregates Crushing Values	Impact value	Abrasion Value
Experimental aggregates	25.5	9.8	25.8
Portland Emco	20	11	29.04

Cold Asphalt	Aggregates Crushing Values	Impact value	Abrasion Value
UPM	20.35	14.99	29.02
Carboncor	20.8	10.6	25.48
Standard Value	Not Exceeding 30	Not Exceeding 15	Not Exceeding 30

3.3. Comparison of available cold asphalt in Nigeria with DPWS modified cold asphalt

The properties of the available cold mixes in Nigeria were compared to the experimental asphalts. The following were inferred from the conducted laboratory analysis.

3.3.1. Sieve analysis

The sieve analysis chart, illustrated in Figure 4 for the four considered cold asphalt samples, indicates that the gradation of DPWS-modified cold mix asphalt contains a balanced distribution of fines and coarse particles, adhering closely to the grading specifications outlined by the Nigerian General Specification [23]. This finding is similarly observed in the case of Carboncor cold asphalt. However, the gradation of Portland Emcol cold asphalt exhibits an excess of fine particles and a scarcity of coarse particles. Regarding U.P.M Cold asphalt, both physical observation and sieve analysis reveal a uniform type of aggregates on sieve 2.36 mm, lacking fines and coarse particles, which may hinder effective asphalt binding. All asphalt samples can be considered fully stable if not exposed to air. Upon exposure, U.P.M demonstrates slow-setting characteristics, while the others exhibit a medium-setting nature. Additionally, according to literature, the asphalt samples are classified as anionic due to their interaction with water and their effective binding with aggregates.

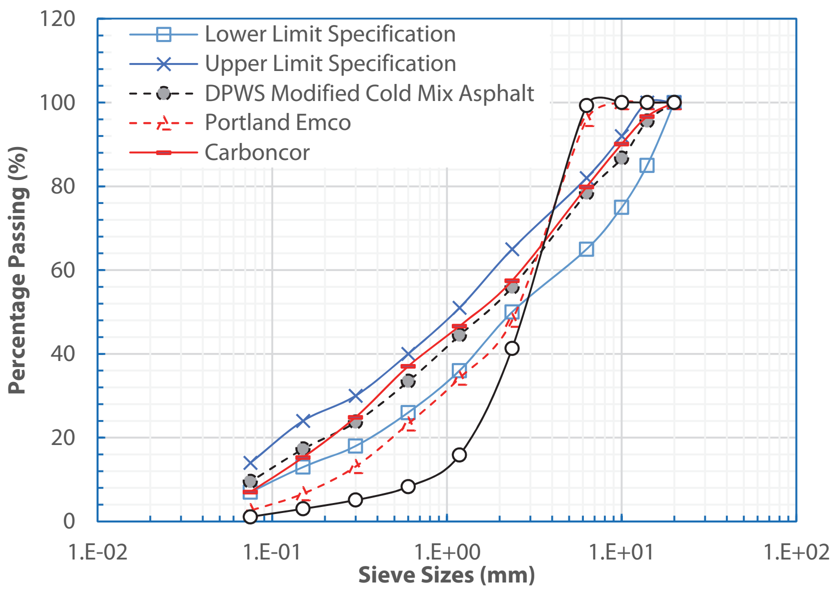

Figure 4: Combined gradation chart for four cold mixes

3.3.2. Bitumen content

The bitumen content of the cold asphalt samples is detailed in Table 5. The findings reveal that none of the cold asphalt samples meet the recommendations outlined in the Nigerian General Specifications [23] for hot mix. However, considering literature studies that specify a range of 1 – 10%, both the DPWS modified cold mix asphalt and U.P.M fall within the specified range. In contrast, Portland Emco and Carboncor asphalt slightly exceed the specified range [26].

Table 5: Determination of bitumen content for all samples

Samples	Experimental Asphalt	Portland Emcol	Carboncor	UPM
weight of sample before extraction, g, (A)	988	1178.7	1008.8	1063.3
weight of sample after extraction, g, (B)	906	1067.0	906.7	969.6
weight of bitumen, g, (C) = A – B	82	110.8	102.1	93.7
% bitumen by weight of total mix = C/A X 100	8.3	9.4	10.1	8.8
% bitumen by weight of aggregate = C/B X 100	9.1	10.4	11.3	9.7

3.3.3. Specific gravity

Table 6 displays the specific gravity of the aggregates constituting the different cold mix asphalt mixes. The values for all aggregates fall within the range of 2.42 – 2.68, complying with the specifications for crushed aggregates. This property, in conjunction with particle size gradation, implies that the commercial cold mix asphalts were manufactured in accordance with global best practices, and the DPWS experimental asphalt aligns similarly.

Table 6: Specific gravity of the various samples

Material		Experimental Asphalt [g]	Portland Emcol [g]	Carboncor [g]	U P M [g]
Wt of cylinder (A)		185.5	114.10	126.90	97.50
Wt of Cylinder + Sample (B)		323.6	208.40	217.8	161.7
Wt of cylinder + Sample + Water (C)		940.7	421.80	428.30	386.20
Wt of cylinder + water only (D)		858.9	362.4	374.9	346.0
Specific gravity [g/m^3]	$\frac{(B-A)}{(D-A)-(C-B)}$	2.45	2.59	2.42	2.68

3.3.4. Marshall test

Tables 7 and 8 provide a comprehensive overview of the strength properties for various samples of cold mix asphalts, comparing them with the standards set for hot mix asphalts. Table 7 presents the strength properties using the standard test method for asphalt specimens, while Table 8 outlines the results for the air-dried asphalt testing method. It is noteworthy that the samples exhibited elevated stability values under the conditions of the latter testing method.

3.3.5. Stability

The stability values of the different cold mix samples, as presented in both Table 7 and Table 8, indicate that Experimental, Portland, and Carboncor samples conform to the standard specifications for hot mix. In contrast, the UPM sample fails to meet the standard specification. Notably, the stability values for the Experimental and Carboncor samples significantly surpass the minimum requirement, as outlined in Table 7. For the UPM sample, stability could not be tested using the standard method; however, a value of 1 kN was obtained when air-dried, as indicated in Table 8.

3.3.6. Flow

The flow values for the various cold mix samples are outlined in Tables 7 and 8, presenting results for two distinct testing methods (normal asphalt and air-dried asphalt methods). Table 7 displays the outcomes of the standard testing method for asphalt. Notably, DPWS cold mix asphalt and Portland Emcol conform to the peak of the specification, while Carboncor asphalt falls outside the specified range. The flow for UPM asphalt cannot be determined due to the material's inability to bind when immersed in water. However, when the air-dried method is employed (Table 8), none of the samples exhibit flow values within the range specified for hot mix. Portland Emcol and experimental asphalt samples slightly exceed the specified range. Notably, the UPM sample demonstrates the highest flow value, surpassing the range for hot mix standard in the air-dried testing method, further confirming the suboptimal nature of the sample.

3.3.7. Voids in total mixture

Analysis of Tables 7 and 8 reveals that the percentage voids in the total mixture for all the samples surpass the specified range for hot mix standard across all testing methods. This observation underscores the porous characteristics of the samples during testing, attributed to the gradual dissipation (dissolving) of the bitumen binder in the mix over time.

Table 7: Comparison of test results for normal asphalt method of testing

Property	Cold mix Asphalt				Standard specification for hot mix wearing course	Remarks
	Experimental Asphalt	Portland Emcol	Carboncor	UPM		
Bitumen content [%]	9.10	10.40	11.30	9.70	5.0 - 8.0	Excessive
Stability (kN)	5.80	2.21	4.27	-	≥ 3.5	Only Experimental and Carboncor are adequate

Property	Cold mix Asphalt				Standard specification for hot mix wearing course	Remarks
	Experimental Asphalt	Portland Emcol	Carboncor	UPM		
Flow (mm)	4.0	3.95	5.5	-	2 – 4	High flow
Voids in total mixture (%)	10.79	17.43	17.97	32.90	3 – 5	Too porous hence high oxidation
Voids filled with bitumen (%)	51.76	49.74	46.31	30.45	75 – 82	In adequate
Density	1.94	1.88	1.73	1.60		

Table 8: Comparison of test results for air-dried asphalt mixes

Property	Cold mix Asphalt				Standard specification for hot mix wearing course	Remarks
	Experimental Asphalt	Portland	Carboncor	UPM		
Bitumen content [%]	9.1	10.40	11.30	9.7	5. - 8.0	Excessive
Stability [kN]	9.58	4.37	9.79	1.00	≥ 3.5	All adequate except UPM
Flow [mm]	4.5	4.85	5.5	6.85	2 - 4	Weak and high flow
Voids in total mixture [%]	12.30	16.18	21.27	29.65	3 - 5	Too porous hence high oxidation
Voids filled with bitumen [%]	49.02	51.98	41.74	33.96	75 - 82	In adequate
Density	1.90	1.96	1.72	1.70		

3.3.8. Voids filled with bitumen

The percentage of voids filled with bitumen in all cold mix samples consistently registers below the specified range for standard hot mix asphalt across all testing methods. Inadequate bitumen content in a mix signifies material compaction, posing a risk of shortened pavement lifespan. These findings indicate a potential necessity for the development of new standards specifically tailored for cold asphalt. This would ensure robust quality control for cold pavement repairs, an area gradually gaining prominence in the Nigerian market.

3.4. Performance characteristic of asphalts mixes (laboratory and field evaluation)

3.4.1. Sieve analysis

Upon examining the behavior of all the cold asphalt samples in Figure 5, it is evident that when loads are applied to the asphalts, they settle rapidly in the initial few minutes and later gain strength against the load but continue to settle at a slower rate. This phenomenon is consistent across all samples.

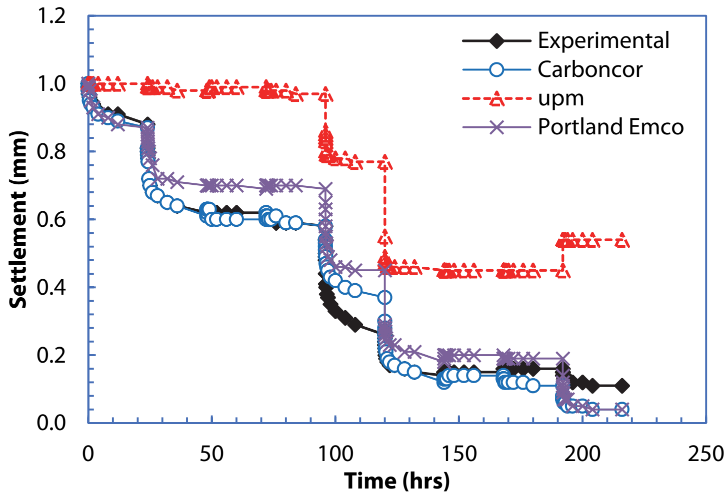

Figure 5: Settlement of four cold asphalt after 9 days

Also depicted in Figure 6 are the reductions in voids against loading for all the samples. This scenario illustrates the gradual disappearance of voids in the asphaltic mix with loading, consequently reducing the thickness of the asphalt and rendering it incapable of withstanding the imposed traffic loading due to continuous thickness reduction. This suggests that if loadings are known, and the settlement rate is determined, the pavement lifespan can be estimated at the time of construction. Therefore, it is imperative that roads, when constructed, account for settlement rates. In this case, settlement rates against loading were calculated as Cr (initial compression), Cc (compression index), av (volume compressibility), and magnitude of settlement after 20 years for the four sampled as determined from the figures.

For experimental cold mix asphalt, Cr was determined to be 0.0029, Cc was 0.0149, av was 0.000209, while the magnitude of settlement after 20 years was 4.33mm. Carboncor cold mix asphalt exhibited Cr as 0.004, Cc as 0.0199, av as 0.000209, with a magnitude of settlement after 20 years at 5.50mm. UPM cold mix asphalt displayed Cr as 0.00, Cc as 0.1661, av as 0.000219, and a magnitude of settlement after 20 years at 4.71 mm. For Portland Emco cold mix asphalt, Cr was 0.004, Cc was 0.0183, av was 0.000262, and the magnitude of settlement after 20 years was 5.11mm.

The above values imply the rate of deformation of the asphalt. It was observed that all the cold mix asphalts are within an allowable range of settlement, with the experimental mix showing the best performance. The slope of the experimental cold mix asphalt was categorized into three parts: the primary settlement of 0.48%, which is a rapid settlement when roads are just open to traffic; the secondary settlement of 0.0101%, which follows the primary settlement but is gradual; and the third settlement of 0.00909%, which is very slow but results in pavement failure. The same trend applies to other mixes except UPM cold mix, which attempts to buckle before its eventual failure.

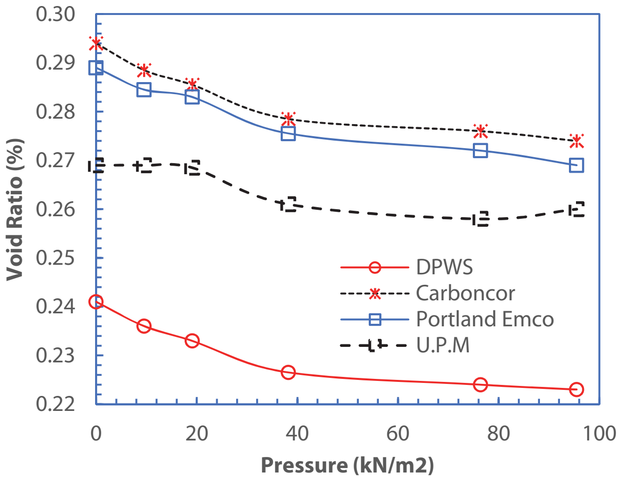

Figure 6: Void reduction against pressure for different cold mix asphalt

3.4.2. Field settlement evaluation base on traffic

From Figure 7 and Figure 8 the asphalts settle with increase in time which is in accordance with the standard specification. From Figure 7, one can also deduce the rate of settlement, the DPWS modified cold mix asphalt settles at 0.0086mm/week, Carboncor settles at 0.114mm/week, Portland Emco has its own settles rate at 0.0129mm/week while the UPM has a settlement rate of 0.0157mm/week.

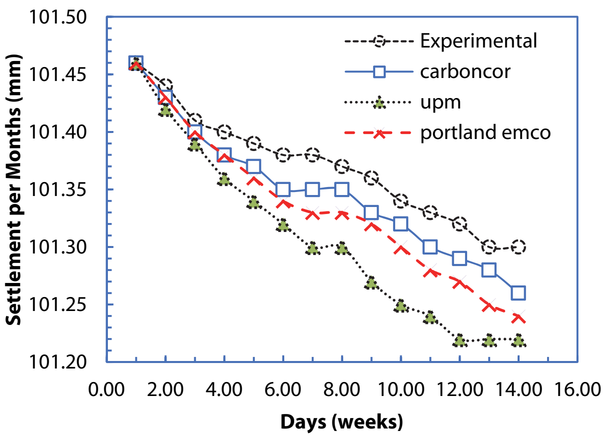

Figure 7: Trend of settlement for cold asphalt mixes

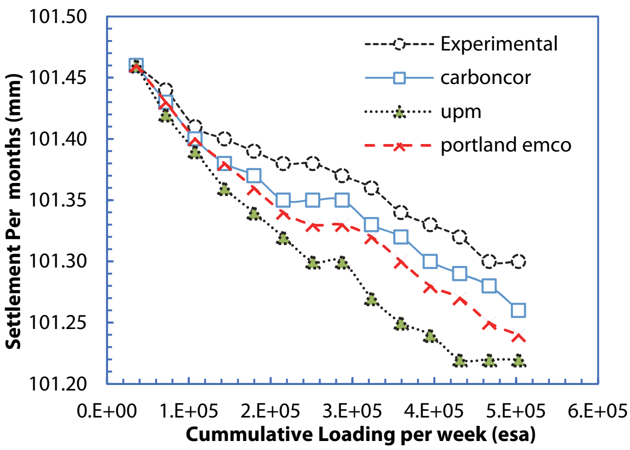

Figure 8: Settlement of cold asphalt due to axle loading

Though, this settlement diminishes with time, but this happens at mid-experimental stage. This also translate to 0.0000877mm/axle load for experimental asphalt, 0.0000785mm/axle load for Carboncor, 0.0000581mm/axle load for Portland Emco while UPM has 0.000071mm/axle load per week. In Figure 8, it could be seen that the DPWS modified cold mix asphalt has ability to withstand traffic loading more than other types of cold mix asphalts while Portland Emco and Carboncor has considerable strength, UPM has the least.

3.4.3. Hardening results

Due to the setting of asphalt, it is expected that there should be an increase in its rate of hardening with time in order for it to meet the specification of a good asphalt sample. All the used asphalts meet the standard specifications, since the samples exhibited a steady increase in their strength properties with a constant increase in time as shown in Figure 9. However, the DPWS modified cold mix asphalt seem to be the better of all with 32kN/m^2 and closely followed by Carboncor with an average maximum strength of 26 kN/m^2, while the Portland Emco has 17 kN/m^2 and UPM is the lowest in strength with 13 kN/m^2. This shows that the DPWS modified asphalt cold mix asphalt is the best in terms of gaining strength with time. In term of rate of hardening the DPWS cold mix asphalt sets faster at rate of 110 % hardening rate per week follow by Portland Emcol with 100 % hardening rate per week, while Carboncor and UPM has 75% and 12.3% hardening rate per week, respectively.

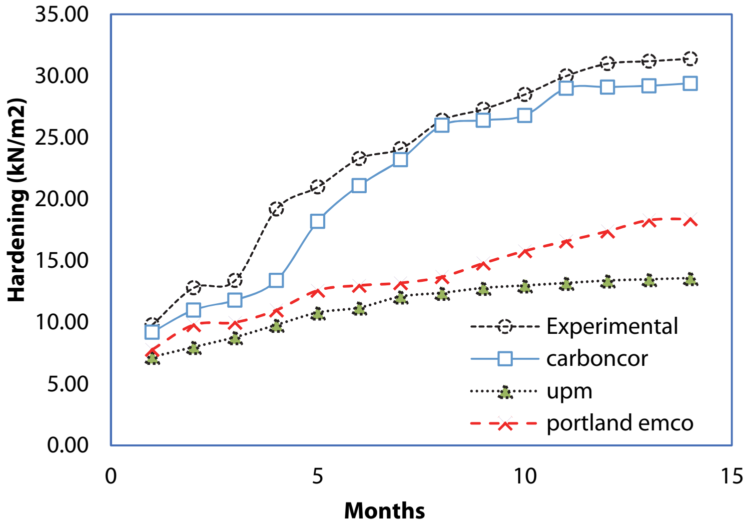

Figure 9: Hardening of test cold asphalt

3.4.4. Rheological properties

This property of materials shows how well mixed the asphalt samples are, the properties also show the ability of the asphalt to return to shape after loading. Table 9 shows that all the materials are well mixed (good) and have the ability to return to shape after load applications. This also goes to confirm Figure 6 to Figure 9 which shows that the asphalt materials are elastic.

Table 9: Rheological properties of experimental and sample asphalts

Sample Type	Sample Nos	Transit Time (Ns)	Path Length (mm)	Velocity (m/s)	Elastic Modulus (GN/m^2)	Average Elastic Modulus (GN/m^2)	Pulse Velocity	Average Pulse Velocity
Experimental Asphalt	D	48.2	192	10,375	78.5	52.9	3.98	3.98
	E	53.2	212	9,398	42.1		3.98	
	F	53.9	215	9,276	38.2		3.99	
Carboncor Asphalt	A	48.2	192	10,373	79.3	86.05	3.79	3.85
	B	31.8	127	15723	92.8		3.87	
U.P.M Asphalt	G	45.6	182	10,964	99.4	78.3	3.99	4.0
	H	48.3	193	10,351	80.1		4.00	
	I	51.3	205	9,746	57.3		4.00	
Portland Emco Asphalt	J	42.3	169	11,820	16.3	22.65	3.90	3.90
	L	41.3	165	12,106	29.0		3.90	

4. CONCLUSION

Thereafter, the performance of the DPWS cold mix asphalt was valued with three commercial ones already in use in Nigeria to ascertain what its performance would be when compared with those in use in the country in a typical subtropical region. These performance characteristics were monitored with Marshall physical and mechanical properties under laboratory and field/traffic loadings for a period of 14months. The four cold mix asphalts were also subjected to nondestructive testing to determine the modulus of elasticity, resilient modulus and other consistency test using the PUNDIT apparatus. The physical properties of the DPWS cold mix asphalt were comparable with other cold mixes, with the bulk density respectively for experimental asphalt, Portland Emcol, Carboncor and UPM of 1.93 g/cc, 1.88 g/cc; 1.74 g/cc and 1.6 g/cc, an indicating that the experimental asphalt is the heaviest.

It was discovered that the DPWS cold mix asphalt in general behaves as an elastic material and consolidates like a saturated clay with time and traffic loading with characteristic values of initial compression, compression index and volume compressibility of 0.0029 mm, 0.0149 and 0.00209 m2/kN respectively. The Carboncor cold mix asphalt corresponding elastic deformation /consolidation properties are 0.004 mm, 0.0199 and 0.000209 m2/kN. The other two commercial cold mix asphalts are less favourable and in the range 0.00 – 0.004 mm, 0.0183 – 0.166 and 0.000219 – 0.000262 m2/kN correspondingly. In terms of hardening rate, the DPWS cold mix asphalt seem to be the best of all with average maximum strength 32 kN/m2 and closely followed by Carboncor with a value of 26 kN/m2, while the Portland Emcol has 17 kN/m2 and UPM is the lowest in strength with 13 kN/m2. NDT determined dynamic elastic modulus of the DPWS modified cold mix asphalt was 52.9 GN/m2 on the average, while the corresponding values for commercial cold mix asphalts were in the range of 22.65 – 86.05 GN/m2. In most of the mechanical properties examined, that is, gain in strength with time, rate of hardening; the DPWS cold mix asphalt proved to be superior.

Based on the outcome of both field and laboratory tests and analysis / comparison of the performance of various cold mix asphalts with regard to hot mix specifications and standard, the following recommendations were drawn: - Aggregates for cold mix asphalt should be well distributed with different aggregate sizes. Air-drying should be used as a method of curing in cold asphalt. A standard be introduced for cold mix asphalt instead of using the hot mix standard as the bench mark for evaluation. Cold mix asphalt can be considered for minor jobs, maintenance and repairs at normal air temperature. Production of feasible and less energy demand cold mix asphalt with non-degradable polythene sachet wastes should be encouraged by first dissolving the wastes under a temperature range of 80 – 120ºC, mix with straight run bitumen, alkaline/acid emulsifier and water to produce the cold mix emulsion. The use of UPM cold mix asphalt should be subjected to further study in Nigeria as its effectiveness.

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