STATE OF ART LITERATURE REVIEW ON THE MECHANICAL, FUNCTIONAL AND LONG-TERM PERFORMANCE OF COLD MIX ASPHALT MIXTURES

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ABSTRACT

Road networks play a vital role in both the social and economic development of a country, however, the engineering techniques used to design and maintain pavements are heavily funded by the extensive use of money, energy and raw materials. The necessity for effective sustainable road networks with the capability of supporting higher traffic loads is evident in expanding and developing cities. With recent technological advancements in the asphalt industry, cold mix asphalt is sought as the new approach to a more sustainable form of asphalt due to its reduced embodied energy mainly achieved through the absence of having to heat constituent materials at such high temperatures which in turn decreases overall construction costs. Over the last three decades, more new innovative modifiers have been used within cold mix asphalt demonstrating improvements in mechanical properties, some of which outperformed conventional hot mix asphalt. This state of art review concentrates on the mixture parameters, the functional and mechanical properties of various cold mix asphalt specimens, both modified and unmodified, while providing insight on the use and effect of a range of modifiers.

1. INTRODUCTION

Conventional asphalt is a mixture of aggregate, filler and binder typically used in the construction and maintenance of pavements (Al-Busaltan *et al.*, 2012; European Asphalt Pavement Association, 2020; Jain and Singh, 2021). In some instances, additives such as modifiers, adhesion agents and fibres may be incorporated within the mixture to provide specific enhancements to the performance of asphalt (Attaran Dovom *et al.*, 2019; Boateng *et al.*, 2022;

Abbreviations: B: Pure bitumen, P: Polymer modified bitumen, M: Mixed modified bitumen, C: Cement modified bitumen, Em: Emulsifier, PG: Performance/penetration grade, Pen: Penetration grade, SP: Softening point, Bit: Bitumen, RS: Rapid setting, MS: Medium setting, SS: Slow setting, UCO: Used cylinder oil, FP: Flashpoint, Duct: Ductility, KV: Kinematic viscosity, DV: Dynamic viscosity, OEC: Optimal emulsion content, PTV: Pendulum test values, RAPB: Readily available pre-bagged, LCF: longitudinal coefficient of friction, IDT: Indirect Tensile Strength Test, SM: Stiffness modulus, C_s: Creep stiffness, G*: Complex shear modulus, ITSM: Indirect tensile stiffness modulus, CS: Compressive strength, S: Stability, RM: Resilient Modulus, PD: Permanent deformation, , OPC: Ordinary Portland cement, TSR: Tensile strength ratio, VC: Void content, ID: Identification, Diam: Diameter

Kong *et al.*, 2022). Asphalt is notable for its dark-brown to black colour attained by the binder bitumen used to cement aggregate together (Chen, 2018; Loeschen, 2019; Dulaimi *et al.*, 2020).
The most common type of asphalt manufactured for paving roads is hot-mix asphalt which is both energy and cost extensive (Thives and Ghisi, 2017; Huang *et al.*, 2019). Produced and reaching job sites at temperatures between roughly 150°C and 180°C, an estimate for the total energy consumption of each single-lane width kilometre-long section of hot mix asphalt roadway is between 2 to 4 terajoules (Pavement Interactive, 2012; Mrugacz, 2014). Nevertheless, with the benefit of technological advancements within the asphalt industry, two sustainable types of asphalt have been developed. Warm mix asphalt, which heats constituent materials to lower temperatures of between 110°C and 140°C, and the most sustainable asphalt variant up to date being cold-mix asphalt where no heat is used (Zaumanis, 2014; Srikanth, Kumar and Vasudeva, 2019; Alzerjawi, Mahdi and Hamza, 2020; Highways England, 2021; Saad *et al.*, 2021). The production of asphalt that requires no heat is only possible through the use of the binder bitumen emulsion (European Asphalt Pavement Association, 2007).
Bitumen emulsion is a mixture of bitumen and water put together by the use of an emulsifier (Rahman, 2017; Chunduri *et al.*, 2022). The emulsion breaks either during the mixing of materials put together or during compaction of the mixture which results in bitumen coating the aggregate. Breaking is the process of water being removed from the asphalt mixture hence causing strength gain over time through the coalescence and cohesion of the bitumen particles (Ziyani, Hammoum and Deneele, 2014; Padhi, 2016; Laurén, 2020; Zhao *et al.*, 2022). During the breaking of bitumen emulsions, cold-mix asphalt takes on the properties of hot-mix asphalt however taking longer period of time as well as not being as durable as both hot-mix or warm-mix asphalt. For this reason, the mixture is generally used in low traffic volume areas (Shinwari, 2012; Shanbara *et al.*, 2021; Usman *et al.*, 2022).

2. MAIN BENEFITS AND CHALLENGES

Cold-mix asphalt is an economically, environmentally, and socially beneficial approach to the construction and maintenance of pavements. It is suitable for use in a variety of climates; has better workability than both hot and warm-mix asphalt; can be deemed as safer for use with tradesmen not having to be in contact with high-temperature asphalt as well as being emission-free; and it being significantly cost-effective primarily by not having to heat the mixture or dry the aggregates (Shinwari, 2012; McAsphalt, 2019; Dash, Chandrappa and Sahoo, 2021; Sun *et al.*, 2022). Consequently, a problem with not heating constituent materials is the extended period of the mixture's curing process due to the presence of water trapped within the mixture which causes cold mix asphalt to have a weak early life strength (Dulaimi *et al.*, 2022; Zhao *et al.*, 2022). It is therefore said that in general, a section of road made with cold-mix asphalt has a longer curing time to achieve mechanical properties safe for traffic to pass through than as compared to hot-mix asphalt which after compaction and cooling is safe to be opened to traffic within 100 to 270 minutes (Serfass *et al.*, 2004; Saadoon, Garcia and Gómez-Meijide, 2017; Alenezi, García and Norambuena-Contreras, 2018). In addition, it is claimed that the high air-void content of compacted cold mix asphalt affects both its mechanical performance and long-term durability properties such as its susceptibility to free-thaw conditioning although some papers state otherwise (Jendia and Jarada, 2006; Thanaya, Zoorob and Forth, 2009; Redelius *et al.*, 2012).

3. AIM AND OBJECTIVES

The review paper was created with the aim to critically examine the development of cold mix asphalt mixtures in the last three decades. To succeed in achieving the aim, this paper will meet the following objectives:

[1] Evaluate the development and progression of cold mix asphalt mixtures in the last three decades.
[2] Analyse the mixture parameters of various modified and unmodified cold mix asphalt specimens
[3] Review the application, laboratory and field performance of cold mix asphalt mixtures in terms of functionality, resistance to cracking, and rutting including durability against both water and ageing.

4. PART 1: REVIEW ON CONSTITUENT MATERIAL (EMULSION)

4.1 DEVELOPMENT OF EMULSIONS

Although both the use and production of bitumen emulsions had started as early as the beginning of the 20th century, the use of bitumen emulsion within asphalt production to produce cold mix asphalt is a fairly new concept. Consequently, papers and articles regarding the use of bitumen emulsions within cold mix asphalt are mainly limited to the last three decades. Nevertheless, a variety of papers and articles have been produced providing some fruitful information regarding different aspects of both modified and unmodified bitumen emulsions from across the world. A variety of modified and unmodified bitumen emulsions, each having been given a unique designation

ID number for use as a reference within the paper and ordered in chronological order, were used to produce cold mix asphalt specimens. The different emulsions can be seen referenced below in Tables 1, 2 and 3 along with some essential data including the country of production and testing, or even the additives used. It can be seen that a fair number of emulsions are modified with a type of cement and that positively charged emulsions, hence cationic emulsions, are the most sought after while the most common bitumen content percentage is 60%. The type and quantity of modifier or additive used has an effect on the properties of bitumen emulsion such as the softening point and penetration depth of bitumen emulsion residue as was seen with the variants of emulsion P6.

Reference	Country	Emulsion name	Additives/Em	Base binder PG, Pen, SP	Bit %	ID
(British Standards, 2009; Redelius *et al.*, 2012; Redelius, Östlund and Soenen, 2016)	Sweden	Cationic Slow-breaking, Nymix 630	+2% Breaking Additive	160/220, 33°C	-	B1-1
		Cationic Slow-breaking, Nymix 240		330/430, 39°C		B1-2
(British Standards, 2009; Ziyani, Hammoum and Deneele, 2014)	France	Bitumen Emulsion	Polyamine Em	160/220, 206mm, 38.8°C	65	B2
(British Standards, 2009; Miljkovic, 2014)	Germany	Cationic	Cationic Em	20/30, 60°C	60.9	B3-1
				50/70, 50.7°C	60.8	B3-2
				70/100, 48.1°C	61.0	B3-3
				160/220, 39.2°C	60.9	B3-4
(British Standards, 2009; Day, Lancaster and McKay, 2019)	UK	Cationic – Nynas 40/60 - C60B5 Emulsion	-	40/60, 48-56°C	-	B7

Table 1: Different types of unmodified emulsion

Reference	Country	Emulsion name	Additives/Em	Base binder PG, Pen, SP	Bit %	ID
(Vivier and Brule, 1992)	France	Polymer Modified SS Cationic	Polyacrylonitrile - 0.1-0.2wt% of dry aggregate, ethylene vinyl acetate polymer	-	-	P6
(Chavez-Valencia *et al.*, 2006; American Society for Testing and Materials, 2009)	Mexico	Cationic Quick Setting	-	63mm, 42°C	62.65	P2-1
		Cationic Polyvinyl Acetate	Polyvinyl Acetate	63mm, 39.5°C	62.56	P2-2
(Borhan *et al.*, 2007; Bitumina, 2013)	Malaysia	80/100 Penetration Grade	-	80/100, 73mm, 49.4°C	-	P3-1
		UCO modified	20% UCO	80/100, 212mm, 34.1°C		P3-2
			25% UCO	80/100, 294mm, 31.2°C		P3-3
			30% UCO	80/100, 382mm, 28.3°C		P3-4
		CSS-1h Cationic SS	-	-	61	P7-1

(Tavassoti, Solaimanian and Chen, 2022)	Canada, USA	CSS-1hp Cationic SS Polymer Modified	Polymer	-	62	P7-2
(Xu *et al.*, 2021)	China	SBS Modified Emulsified Cationic Bitumen	SBS polymer	68mm, 62.5°C	60	P8

Table 2: Different types of polymer-modified emulsions

Reference	Country	Emulsion name	Additives/ Em	Base binder PG, Pen, SP	Bit %	ID
(Ojum, 2015; Nynas, 2020)	UK	Cationic – Nymuls CP 50	-	47mm, 52°C	60	M1-1
			1% Cement			M1-2
			3% Cement			M1-3
(Fang *et al.*, 2015)	Switzerland	Modified Anionic	Cement, Rosin Em	-	60	M5-1
			Rosin Em			M5-2
(Fang, 2016)	UK	Cement Modified Cationic	Rapid-hardening Cementitious Material	24mm, 63.6°C	60	C1-1
		Cement Modified Anionic		41mm, 58.5°C		C1-2
(British Standards, 2009; Snedden, 2018)	UK	Probit CAB 50-70	-	50/70, 46-54°C	-	M2-1
			2% Cement			M2-2
(Lonbar and Nazirizad, 2016; Ling and Bahia, 2018)	USA	Cationic SS	-	76mm, 61.4°C	57.2	M3-1
			Unspecified Modifier			M3-2
			1.5% Cement			M3-3
			3.0% Cement			M3-4
(Arshad *et al.*, 2018)	Malaysia	ACP-DMT	-	-	61.8	M4-1
			2% Cement			M4-2
(Li *et al.*, 2020)	China	Cationic SS 60/70	0% cement	60/70, 64.5mm, 50°C	63.0	M7-1
			2% cement			M7-2
			4% cement			M7-3
			6% cement			M7-4
(Yang *et al.*, 2021)	China	Cationic SS	0% Cement, 3% Limestone powder	55.1mm, 48.8°C	60	M6-1
			1% Cement, 2% Limestone powder			M6-2
			2% Cement, 1% Limestone powder			M6-3

Table 3: Different types of mixed-modified emulsion

5. PART 2: MIXTURE PARAMETERS, FUNCTIONAL AND MECHCNAIL PROPERTIES OF COLD MIX ASPHALT

5.1 MIXTURE PARAMETERS OF COLD MIX ASPHALT

The mixture parameters of asphalt play such an influential role in gaining the desired properties of a specimen. Changes in constituent material parameters such as the bitumen grade, aggregate type or mixture gradation have to be carefully chosen to avoid producing detrimental properties within an asphalt specimen. Tables 4, 5 and 6 present the mixture parameters of various cold mix asphalt specimens, such as the aggregate and filler type used, providing insight into what parameters were sought after or avoided overall. Brief summaries are provided after each table rounding up and analysing the data drawing comparisons, patterns and differences between different modified and unmodified cold asphalt mixture parameters.

5.1.1 MIXTURE PARAMETERS OF UNMODIFIED COLD MIX ASPHALT SPECIMENS

A good range of different bitumen grades are included in Table 4 with 160/220 penetration grade being the most commonly used grade. Although no data was provided for optimal emulsion content percentages, emulsions B1.1 and B1.2 declared a binder content of 5.5% in respect to the overall mix by mass of dry aggregate and filler. As for the bitumen content percentage within the emulsion and the type of aggregate used within mixtures, emulsion B2 recorded a bitumen content of 65% while the variants of emulsion B3 together averaged a slightly less bitumen content of roughly 61%. The mixture produced with Emulsion B2 comprised of gneiss, diorite and limestone aggregate while the mixtures made with the variants of emulsion B3 used limestone and natural quartz sand. Therefore, both the emulsion B2 and the variants of emulsion B3 mixtures desired the inclusion of limestone aggregate with the variants of emulsion B3 mixtures further stating the use of limestone as a filler while no data was provided by the remaining mixtures. The variants of emulsion B3 and B1 recorded the nominal maximum size of aggregate as 32mm and 16mm respectively while both having an open graded mixture gradation. Emulsion B2 mixtures recorded having a slightly lower nominal maximum aggregation size of 10mm while comprising a dense 0/10mm mixture gradation in comparison to the open gradations of emulsions B1 and B3 mixtures.

ID	Mixture parameters							
	Emulsion type	**OEC (%)**	**Binder content (%)**	**Bit Content (%)**	**Aggregate type**	**Nominal maximum size (mm)**	**Filler type**	**Mixture gradation**
B1-1	160/220	-	5.5 - by mass of dry aggregate and filler	-	-	16	-	Open
B1-2	330/430							
B2	160/220	-	-	65	Gneiss, Diorite, Limestone	10	-	Dense - 0/10mm
B3-1	20/30	-	-	60.9	Limestone, natural quartz sand	32	limestone	Open
B3-2	50/70			60.8				
B3-3	70/100			61.0				
B3-4	160/220			60.9				

Table 4: Mixture parameters of unmodified cold mix asphalt specimens

5.1.2 MIXTURE PARAMETERS OF POLYMER MODIFIED COLD MIX ASPHALT SPECIMENS

The polymer modified emulsions below in Table 5, along with emulsion P2.1 and P7.1 being unmodified however used as a reference against their polymer modified counterpart emulsions P2.2 and P7.1 respectively, together provided data concerning mixture parameters such as aggregate type used. While the variants of emulsion P2 together used a 64-22 grade emulsion, emulsion P3 used an 80/100 penetration grade emulsion with emulsions P6, P7.1, P7.2 and P8 only stating the use of a slow setting cationic emulsion. Mixtures made with the polymer modified emulsion P8 noted an optimal emulsion content of 8%, being more than two times high than of the mixtures made with the P7 emulsion. No data was supplied concerning the binder content used within the mixtures. Nevertheless, emulsion P2.1, P2.2, P7.1, P7.2 and P8 recorded bitumen content percentages of 62.65%, 62.56%, 61.0%, 62.0% and 60.0% respectively. Each mixture used a different type of aggregate while disregarding the mixture made with emulsion P6 where no data was supplied for the aggregate used. The variants of emulsion P2 and P7 used siliceous aggregate and reclaimed asphalt pavement correspondingly within their mixtures while mixtures produced with emulsion P3 and P8 separately used granite and basalt aggregate. The specimens produced with Emulsion P6 did however provide insight to having a nominal maximum size aggregate of 10mm and comprising a 0/6mm to 0/10mm gap gradation. The aggregate used within the mixture produced with emulsion P8 recorded having a nominal maximum size of at least 13.2mm but less than 16mm while using limestone mineral powder and cement as filler to produce the continuous dense gradation AC-13.

ID	Mixture parameters

	Emulsion type	OEC (%)	Binder content (%)	Bit Content (%)	Aggregate type	Nominal maximum size (mm)	Filler type	Mixture gradation
P2-1	64-22	-	-	62.65	Siliceous aggregate	-	-	-
P2-2				62.56				
P3	80/100	-	-	-	granite	-	-	-
P6	Cationic SS	-	-	-	-	10	-	Gap graded - 0/6mm to 0/10mm
P7-1	CSS-1h	2.5-3.0	-	61.0	Reclaimed asphalt pavement	-	-	-
P7-2	CSS-1hp			62.0				
P8	SBS Modified Cationic SS	8.0	-	60	Basalt	13.2 ≥, <16	Lime stone miner al powd er, ceme nt	AC-13 – continuous dense gradation

Table 5: Mixture parameters of polymer modified Cold Mix Asphalt specimens

5.1.3 MIXTURE PARAMETERS OF MIXED MODIFIED COLD MIX ASPHALT SPECIMENS

Table 6 comprises a great amount of data concerning the mixture parameters of mixed modified cold mix asphalt specimens. The type of emulsion used were made known by emulsion M5 and the variants of emulsions M2, M3, M4, M6 and M7, being distinguished by either the emulsion charge, penetration grade or simply by the emulsion's name. Specimens produced with Emulsion M4.1 and M4.2 provided further detail of the optimal emulsion content being 6.8% and 6.5% respectively while specimens made with the variants

ID	Mixture parameters							
	Emulsion type	OEC (%)	Binder content (%)	Bitumen Content (%)	Aggregate type	Nominal maximum size (mm)	Filler type	Mixture gradation
C1 (1-2)	-	-	-	60	Quartz, sand	8	limest one	Uniform-dense
M1 (1-3)	-	-	-	60	Limestone and sharp sand	20	-	dense
M2 (1-2)	50/70	-	-	-	granite	10	-	dense
M3 (1-4)	CSS-1h	-	-	57.2	Granite, limestone	12.5	-	dense
M4-1	ACP-DMT	6.8	-	61.8	-	14	-	AC14 gradation
M4-2		6.5						
M5	Anionic	-	-	60	-	-	limest one	-
M6 (1-3)	Cationic SS	4.0	-	60	Limestone	-	limest one	Uniform-dense AC-13
M7 (1-4)	Cationic SS	8.0	5.04	63.0	Granite	14	Lime stone miner al	dense

Table 6: Mixture parameters of mixed-modified cold mix asphalt specimens

of emulsion M6 and M7 recorded optimal emulsion contents of 4.0% and 8.0% correspondingly. Although only the emulsion mixtures produced with the variants of emulsion M7 revealing its binder content as 5.04%, the highest and lowest bitumen contents were 63.0% and 57.2% by the variants of emulsions M7 and M3 correspondingly while emulsion, M5 and the variants of both C1, M1 and M6 all recorded bitumen contents of 60%. A range of aggregates were used within mixtures such as granite, limestone and various types of sand however, it is important to note the popular use of granite and limestone in mixtures whether as aggregate or as filler. In addition, a dense gradation is sought after with modified cold asphalt mixtures as shown by the variants of emulsions C1, M1, M2, M3, M6 and M7 with an anomaly being emulsions M4.1 and M4.2 having an AC14 aggregate gradation.

4.2 FUNCTIONAL PROPERTIES OF COLD MIX ASPHALT

The macrotexture and microtextured properties of a cold mix asphalt specimen, such as its skid resistance, are investigated to ensure the production of an adequately safe pavement. Undeniably, a wide range of factors can affect the surface properties of an asphalt specimen ranging from the constituent materials to external factors such as their curing condition. Table 7 outlines the surface properties of modified cold mix asphalt specimens produced with emulsions P6 and M2.2 while the unmodified specimen M2.1 being used as a reference against its modified counterpart. Variables such as the curing conditions were also investigated to observe their effect on the surface properties of a specimen.

ID	Functional Properties		Summary
M2(1-2)	Skid resistance (Pendulum test)	dry conditions	the overall average PTV for the control mix, control mix with 2% cement and RAPB specimens, when cured at different temperatures, were 39, 47.8 and 44.27 respectively
		wet conditions	the overall average PTV for control mix, control mix with 2% cement and RAPB specimens, when cured at different temperatures, were 30.2, 40.13 and 35.65 correspondingly hence being noticeably lower than in dry conditions
	Texture		The overall average texture depths of control mix, control mix with 2% cement and RAPB specimens cured at different temperatures were 0.86mm, 0.88mm and 1.10mm respectively
P6	Appearance		reduced glare
	Texture		Granular surface texture
	Drainage,		improved drainage
	Skid resistance (longitudinal coefficient of friction)		good skid resistance having LCF values comparable or even better than hot mix asphalt At 40,60 and 80km/h, specimens recorded LCF values of roughly 0.61, 0.52 and 0.49 respectively

Table 7: Functional properties of modified cold mix asphalt specimens

When analysing the results from the variants of emulsion M2, the addition of 2% cement positively influenced both the skid resistance and texture depths of the cold mix asphalt specimens. In dry conditions, the cement modified specimens, being emulsion M2.2, recorded an average pendulum test value (PTV) of 47.8 while the unmodified specimens M2.1 recorded an average PTV of 39, lower by 8.8. Furthermore, the same specimens produced with emulsions M2.1 and M2.2 recorded lower pendulum test values in wet conditions than in dry conditions and again, specimens produced with emulsion M2.2 outperformed that of emulsion M2.1 specimens. As for texture depths, specimens made with emulsion M2.2 recorded an average depth of 0.88mm while specimens produced with the unmodified emulsion M2.1 stated an average depth of 0.86mm, lower by a mere 0.02mm. As for the specimens produced with emulsion P6, data was gathered concerning its appearance, texture, drainage and skid resistance. Improvements such as reductions in glare and better drainage were observed by using the modified emulsion P6. Further details can be seen below regarding emulsion P6 and the variants of emulsion M2. The addition of the modifiers used in emulsion M2.2 and P6 both positively enhanced the functional properties of the cold mix asphalt specimens where qualities such as skid resistance were enhanced to the point of performing better than of hot mix asphalt specimens at particular speeds.

4.3 MECHANICAL PROPERTIES OF COLD MIX ASPHALT

A variety of mechanical properties including indirect tensile strengths and stiffness modulus values are contained in tables 8, 9 and 10 below regarding cold mix asphalt specimens. With over 25 different emulsions analysed, productive summaries of the data gathered were produced after each table where patterns and performance statistics are stated comprising a range of different penetration grades with some referencing the emulsion's charge or setting type.

4.3.1 MECHANICAL PROPERTEIES OF UNMODIFIED COLD MIX ASPHALT SPECIMENS

Table 8 comprises a range of mechanical properties such as the indirect tensile strength, creep stiffness and deformation resistance of unmodified cold mix asphalt specimens. Other than stiffness modulus values, no mechanical properties were shared between each cold mix asphalt specimen, nevertheless, valuable information was provided concerning each specimen and their mechanical performance. Emulsions B1.1 and B1.2 assessed the indirect tensile strength (IDT), stiffness modulus (SM), rutting, durability and fatigue cracking characteristics

ID	Property	Performance	
B1-1	Indirect Tensile Strength Test (IDT), Stiffness modulus (SM), rutting, fatigue cracking, durability	Initial IDT: 325kPa Initial SM: 1450MPa	• No noticeable rutting • Good durability • Good resistance to low-temperature cracking • Minimal cracks
B1-2		Initial IDT: 185kPa Initial SM: 750MPa	
B3-1	Creep stiffness (C_s) and Complex shear modulus (G*)	C_s: 546MPa, G* at 30°C: 4E+06Pa	
B3-2		C_s: 246MPa, G* at 30°C: 6E+05Pa	
B3-3		C_s: 139MPa, G* at 30°C: 3E+05Pa	
B3-4		C_s: 57.9MPa, G* at 30°C: 8E+04Pa	
B7	Indirect tensile stiffness modulus (ITSM)	• Lab core specimen's stiffness values stabilised at 6GPa at 10°C which also correlated to site core specimens • Unsealed specimens had a more rapid increase in initial stiffness values than of sealed specimens	
	deformation resistance	• No signs of distress after nearly 10 years of service • Exhibited excellent deformation resistance	

Table 8: Mechanical properties of unmodified cold mix asphalt specimens

of cold mix asphalt specimens. The specimens produced with emulsion B1.1, being a 160/220 penetration grade emulsion, outperformed their counterpart specimens produced with emulsion B1.2, a 330/430 penetration grade emulsion, in terms of initial IDT and SM values. B1.1 specimens recorded initial IDT and SM values of 325kPa and 1450MPa respectively while B1.2 specimens recorded lower values of 185kPa and 750MPa correspondingly. Together, both specimen B1.1 and B1.2 observed no noticeable rutting and minimal cracks while recording good durability and resistance to low temperature cracking. The variants of emulsion B3 evaluated the creep stiffness (S_m) and complex shear modulus (G*) values of specimens. A pattern can be seen between the variants of B3 specimens. As the penetration grade of the emulsion used within the specimens increased, the creep stiffness and complex shear modulus decrease. Specimens created with emulsion B3.1, being the lowest penetration grade of 20/30, recorded a creep stiffness and complex shear modulus value at 30°C of 546MPa and 4E+06Pa respectively while specimens produced with the highest penetration grade emulsions, 160/220 by emulsion B3.4, recorded creep stiffness and complex shear modulus values at 30°C lower than of B3.1 specimens by 488.1MPa and 3.92E+06Pa correspondingly.

Both the indirect tensile stiffness modulus and deformation resistance of emulsion B7 specimens were assessed. It was stated that at 10°C, the lab core specimen's stiffness values were stabilised at 6GPa which also correlated to site core specimens as well as unsealed specimens having a more rapid increase in initial stiffness than of sealed specimens. It can therefore be concluded that B7 specimens significantly outperformed both B1.1 and B1.2 specimens by 4550MPa and 5250MPa respectively in terms of stiffness modulus values. As for deformation characteristics, no signs of distress were observed after approximately 10 years of service hence exhibiting excellent deformation resistance which correlates to B1.1 and B1.2 specimens stating positive observations such as good durability and minimal cracks. On average, the unmodified cold mix specimens showed positive results concerning their mechanical properties such as having good durability and minimal cracks however certain factors such as the penetration grade of bitumen used or the conditions in which the specimens were made and cured heavily effect the mechanical properties of cold mix asphalt specimens.

4.3.2 MECHAINCAL PROPERTIES OF POLYMER MODIFIED COLD MIX ASPAHLT SPEICMENS

The specimens mentioned below in Table 9 are modified with a type of polymer except for specimens P2.1, P3.1 and P7.1 which are unmodified emulsions used as reference against their counterparts. Nevertheless, a range of mechanical properties are assessed including values for compressive strengths, wear resistances and permanent deformation characteristics. When solely observing specimen P2.1, an unmodified specimen, and P2.2, a polymer modified specimen, the addition of a polymer modifier improved the compressive strength as well as both the rutting and fatigue resistances of the specimens. It was also stated that at varying polymer contents, the

ID	Property	Performance	
P2-1	Compressive strength (CS), Rutting and fatigue resistance	At optimal emulsion content, unmodified specimens P2.1 recorded a CS of 12.10kg/cm^2	• The inclusion of modifier PVAC-E improves compressive strength as well as rutting and fatigue resistances of specimens • At varying PVAC-E contents, the CS of P2.2 can be improved by 31% in respect to P2.1
P2-2		• PVAC-E modified specimens P2.2 recorded CS values of 12.10kg/cm^2 and 12.72kg/cm^2 at optimal emulsion contents	
P3-1	Stability (S), Resilient modulus (RM), permanent deformation (PD) and creep stiffness (C_s)	S:10.064kN, Av RM:2625MPa, PD:0.452mm, C_s:67.6MPa	• Generally, has a negative correlation between modifier Used Cylinder Oil (UCO) content and the S, RM and Cs of specimens • Positive correlation between UCO content and PD
P3-2		S:3.550kN, Av RM:736MPa, PD:1.005mm, C_s:35.5MPa	
P3-3		S:5.030kN, Av RM:550MPa, PD:1.007mm, C_s:32.6MPa	
P3-4		S: 3.346kN, Av RM:500MPa, PD:1.007mm, C_s:29.4MPa	
P6	Shear strength and resistance	• Substantial increase in shear strength • Shear resistance doubled, broke after 120mins compared to 60mins by the unmodified control-mix	
	wear resistance	• Noticeable improvement in wear resistance • At 15mins, P6 specimens recorded a wear percentage of less than 1% while the control-mix recorded 14%	
P7-1	Fatigue cracking resistance, dissipated energy ratio (DER), multiple stress creep recovery (MSCR)	• Lower performance than polymer-modified P7-2 specimens in terms of fatigue resistance including cracking resistance, microcracks initiation resistance based on DER values and lower resistance to repeated loading at higher temperatures based on MSCR results	• The addition of 1% Portland cement significantly improves the fatigue cracking resistance of 100% reclaimed asphalt pavement mixtures
P7-2		• Outperformed P7-1 specimens in terms of fatigue resistances, where the fatigue performance of specimens was improved in the range of 166% to 236%, microcracks initiation resistance and its resistance to repeated loading at higher temperatures	
P8	Marshall stability, splitting strength, water stability, rutting performance	• P8 Specimens, being made of a SBS polymer modified emulsion, outperformed the conventional hot and warm mix asphalt specimens in terms of mechanical properties while having a comparable water stability • P8 specimens had excellent rutting resistance in comparison to hot and warm mix specimens • Increasing temperature and load reduces the specimen's rutting resistances sensitivity to load and temperature	

Table 9: Mechanical properties of polymer modified bitumen emulsions

compressive strength of P2.2 specimens could be improved by 31% in comparison to unmodified specimens P2.1. While P2.1 specimens recorded a compressive strength of 12.10kg/cm^2 at optimal emulsion content, P2.2 specimens recorded compressive strength values of 12.10kg/cm^2 and 12.72kg/cm^2 at optimal emulsion contents. As for the specimens made with the variants of emulsion P3, the stability, resilient modulus, permanent deformation and creep stiffnesses were evaluated. A negative correlation was observed between the polymer modifier content and the stability, resilient modulus and creep stiffness of specimens. On the other hand, a positive correlation was seen between the polymer modifier content and the permanent deformation characteristics of specimens. The addition of 30% polymer modifier, as seen in P3.4 specimens, decreased stability, average resilient modulus and creep stiffness values by 6.718kN, 2125MPa and 38.2MPa respectively while permanent deformation increased by 0.555mm all in comparison to the unmodified counterpart specimen P3.1.

The wear resistance, shear strength and shear resistance performance of specimens produced with emulsion P6 were observed. With the addition of a polymer modifier, a substantial increase in shear strength was observed with shear resistance values being doubled where the modified specimens broke after 120mins compared to 60mins by the unmodified control-mix specimens. Moreover, a notable improvement was also noticed in wear resistance figures as the P6 specimens recorded a wear percentage of less than 1% while on the hand, control-mix specimens recorded a wear percentage of 14%. Similarly, the polymer-modified specimens P7-2 outperformed its unmodified counterpart specimen P7.1 in terms of fatigue resistances, microcracks initiation resistance and its resistance to repeated loading at higher temperatures. It was also noted that the addition of 1% Portland cement significantly improved the fatigue cracking resistance of specimens produced with 100% reclaimed asphalt pavement.

Similar to the polymer-modified specimens previously mentioned, P8 cold mix asphalt specimens, being modified with a SBS polymer, outclassed the conventional hot and warm mix asphalt specimens in accordance with their mechanical properties while noting similar water stability properties. While the P8 specimens had excellent rutting resistance figures in comparison to the hot and warm mix specimens, all specimens noticed a reduction in rutting resistance sensitivity to load and temperature when both the environmental temperature and load applied are increased. To conclude, all polymer modified specimens noted clear increases in both wear and deformation resistances excluding P3 specimens which recorded detrimental effects on various mechanical properties such as its resilient modulus and stability.

4.3.3 MECHANICAL PROPERTIES OF MIXED MODIFIED COLD MIX APSHALT SPECIMENS

A wide range of mechanical properties were included in table 10 including deformation resistances, indirect tensile strengths and rutting performances of mixed modified cold mix asphalt specimens. It is important to specifically note that unmodified specimens M1.1, M2.1, M3.1 and M4.1 are solely used as reference against their modified counterparts. When analysing the specimens produced with modified emulsion C1.1 and C1.2, positive results were observed. An improved early life strength was seen in the specimens with further mechanical properties such as its stiffness and stability characteristics being comparable to hot mix asphalt. A positive correlation was also detected between the modifier content and resilient modulus of specimens recording 2700MPa, 8000MPa and 9500MPa at cement levels 2%, 4% and 6% respectively. Again, specimens M1.2 and M1.3, modified with 1% and 3% ordinary Portland cement (OPC) respectively, proved that the addition of cement positively influences the mechanical properties of cold mix asphalt. Substantial improvements were noted in the stiffness and strength properties of specimens where specimen M1.2 on average increased stiffness values by 32% and M1.3 specimens increasing by more than double. In addition, specimens M1.1 and M1.2 recorded improvements in both permanent deformation and fatigue resistances hence outperforming their unmodified counterpart M1.1. An evaluation of the specimens produced with the variants of emulsions M2 noted that all specimens had inadequate strength, both cement modified and unmodified specimens, with almost every specimen failing the indirect tensile stiffness modulus (ITSM) test while the specimens produced using the JP Manufactured mixture with 0% cement recorded unsatisfactory ITSM values.

The indirect tensile strength and stability characteristics of specimens produced with the variants of emulsion M3 were evaluated. It was observed that reasonable mechanical stability can be expected from all the specimens and the addition of cement improves the indirect tensile strength (ITS) of specimens where a positive correlation can generally be seen between the cement modifier percentage and ITS values. With the unmodified specimens M3.1, an ITS value of 0.406MPa was made known while with the 3% cement modified specimen M3.4, an ITS value of 0.582MPa was recorded improving by 0.176MPa. However, with the inclusion of an unspecified modifier seen in M3.2 specimens, a detrimental effect was observed reducing the ITS value by 0.33MPa in comparison to the unmodified specimen M3.1. The Indirect Tensile Strength (ITS), Resilient Modulus (RS) and Rutting performance was determined in specimens M4.1 and M4.2. Cement modified specimens M4.2 dominated the unmodified specimens M4.1 having higher ITS, RS and rutting resistance values than of unmodified specimens M4.1. In reference to the unmodified M4.1 specimens, specimens produced with emulsion M4.2, being modified with cement, had an ITS value higher by 34kPa when unsoaked, an RS value improved by 1252.5MPa and rutting depths lower by 0.032mm, 0.065mm and 0.082mm at 25, 4000 and 8000 repetitions respectively. In terms of ITS values, cement modified specimen M4.2 performed better than both cements modified specimens M3.3 and M3.4 observing ITS values higher by 652kPa and 507kPa correspondingly. However, while unsoaked specimens produced by the variants of emulsion C1 reordered RS values of roughly 2700MPa, 8000MPa and 9500MPa at cement levels 2%,4% and 6% respectively, M4.2 specimens noted its highest RS value as 3808.5MPa hence only performing better than the C1.1 and C1.2 specimens produced with 2% cement.

Specimens produced with the variants of emulsion M6 disclosed the effects of compaction frequency and method on certain mechanical properties. By increasing the compaction blow frequency along with using the double compaction method, a significant reduction in void content can be expected while increasing the specimen's ITS

<table>
<tr><th>ID</th><th>Property</th><th colspan="2">Performance</th></tr>
<tr><td rowspan="3">C1(1-2)</td><td>Strength</td><td colspan="2">• Improved early life strength with the addition of cement</td></tr>
<tr><td>Resilient Modulus (RM),</td><td colspan="2">• Positive correlation between cement level and RM
• At cement levels 2%,4% and 6%, the RM values recorded before soaking the specimens were roughly 2700MPa, 8000MPa and 9500MPa respectively</td></tr>
<tr><td>stiffness and stability</td><td colspan="2">• Mechanical properties such as stiffness and stability are comparable to hot mix asphalt</td></tr>
<tr><td rowspan="3">M1(1-3)</td><td>Stiffness and strength,</td><td colspan="2">• The addition of 1% and 3% ordinary Portland cement (OPC) significantly improves stiffness and strength properties
• M1.2 increased stiffness values by an average of 32%
• M1.3 increased stiffness values by more than double</td></tr>
<tr><td>Deformation resistance</td><td colspan="2">• The addition of OPC improves permanent deformation resistance with M1.2 recording the best resistance followed by M1.3 and M1.1 correspondingly</td></tr>
<tr><td>fatigue resistance</td><td colspan="2">• The addition of 1% and 3% OPC improves fatigue resistance recording strains of less than 200με for M1.2 and M1.3</td></tr>
<tr><td>M2(1-2)</td><td>Indirect tensile stiffness modulus (ITSM)</td><td colspan="2">• All the specimens had inadequate strength with most failing the ITSM test including the JP Manufactured mix with 0% cement recording unsatisfactory ITSM values</td></tr>
<tr><td>M3-1</td><td rowspan="4">Stability, Indirect Tensile Strength (ITS) testing</td><td>ITS: 0.406MPa</td><td rowspan="4">• It was observed and concluded that reasonable mechanical stability can be expected from all the specimens
• The addition of cement improves the ITS value of specimens
• The unspecified modifier has detrimental effects on ITS values</td></tr>
<tr><td>M3-2</td><td>ITS: 0.373MPa</td></tr>
<tr><td>M3-3</td><td>ITS: 0.437MPa</td></tr>
<tr><td>M3-4</td><td>ITS: 0.582MPa</td></tr>
<tr><td>M4-1</td><td rowspan="2">Indirect Tensile Strength (ITS) test, Resilient Modulus (RM), Rutting performance</td><td colspan="2">• M4.1 recorded ITS values of 1055kPa when unsoaked
• highest RM value recorded was 2556MPa
At 25, 4000 and 8000 repetitions, a rut depth of 0.181mm, 2.886mm and 4.379mm was observed respectively</td></tr>
<tr><td>M4-2</td><td colspan="2">• Cement modified specimens (M4.2) have higher ITS, RM and rutting resistances values than of unmodified specimens (M4.1)
• M4.2 recorded ITS values of 1089kPa when unsoaked
• highest RM value recorded was 3808.5MPa
• At 25, 4000 and 8000 repetitions, M4.2 specimens recorded rut depths of 0.149mm, 2.821mm and 4.297mm correspondingly</td></tr>
<tr><td>M6-1</td><td rowspan="3">Indirect Tensile Strength (ITS), failure strain, critical strain energy density (CSED)</td><td>-</td><td rowspan="3">• Increasing the number of compaction blows along with using the double compaction method significantly reduces the void content and increases the ITS and CSED of specimens</td></tr>
<tr><td>M6-2</td><td>• Under the single-curing condition with a low cement content, specimens can obtain high ITS, failure strain and CSED values</td></tr>
<tr><td>M6-3</td><td>• Under the mixed-curing condition and a high cement content, specimens can gain high ITS, failure strain and CSED values</td></tr>
<tr><td>M7(1-4)</td><td>Moisture loss rate, moisture susceptibility resistance, final mechanical performance</td><td colspan="2">• Cement in specimens significantly decreased moisture loss rate while improving early strength, the final mechanical performance and moisture susceptibility resistance
• Larger amounts of cement (4% and 6%) in specimens results in a very high modulus making the mixture very rigid and possibly increasing the mixture's fragility</td></tr>
</table>

Table 10: Mechanical properties of mixed-modified cold mix asphalt specimens

and CSED performance. Depending on the specimen's curing condition, a high

ITS value, failure strain and critical strain energy density can be achieved despite the specimen's cement and limestone powder content. In contrast, specimens produced with the variants of emulsion M7, being modified with varying cement contents, display that the inclusion of cement in specimens significantly decreased the moisture loss rate while improving

the early strength, moisture susceptibility resistance and the final mechanical performance of specimens. It was also made apparent that the inclusion of larger weight percentages of cement within mixtures, in this example being 4% and 6%, resulted in a very high modulus which caused the mixture to become very rigid and possibly increasing the mixture's fragility. In general, the addition of modifiers mentioned within Table 7C, mostly being cementitious material, significantly improves the mechanical performance of cold mix asphalt specimens with certain specimens making a bold claim that its cement modified specimen observed stiffness and stability characteristics comparable to of hot mix asphalt. However, it should be noted that including large amounts of cement within mixtures can be detrimental to its mechanical performance as mentioned in the summary of specimens produced with the variants of emulsion M7.

5 PART 3: LONG TERM FIELD PERFORMANCE OF COLD MIX ASPHALT MIXTURES

5.1 RESISTANCE AGAINST WATER

The moisture susceptibility of an asphalt pavement is the greatest performance concern regarding the durability of an asphalt pavement. It is stated that moisture induced damage of asphalt pavements are an extremely complicated form of stress which leads to reduced stiffness and structural strength hence producing a costly maintenance to the pavement's structure. Table 11 displays moisture sensitivity characteristics such as the moisture resistance, resilient modulus and void contents of various cold asphalt mixtures including details of any modifier used along with the country and year in which the specimens were produced in. Different curing conditions and modified emulsions were used, all of which influenced the moisture sensitivity of cold mix asphalt specimens being evident within the table below.

The test roads produced by the variants of the unmodified bitumen emulsion B1 noted that despite having a high void content, there were no signs of frost cracking hence having sufficient water resistance properties. In contrast, specimens produced with the rapid-hardening cements in C1.1 and C1.2 observed a high-water consumption, solely due to the rapid-hardening cements, hence may reduce the stripping and moisture damage potential of specimens. A large quantity of air voids was also noted which may cause specimens to be susceptible to moisture induced deterioration. While evaluating the tensile strength ratio (TSR) and moisture resistance properties of specimens produced by the variants of emulsion M3, clear results were observed. Specimens produced with the unmodified emulsion M3.1 recorded a poor TSR value of 0.33 while the modified specimens M3.2, M3.3 and M3.4 noted adequate TSR values of 0.86, 0.81 and 0.99 correspondingly hence having an improved resistance to moisture. Similarly, specimens produced with the modified emulsion M4.2 outperformed their unmodified counterpart M4.1 in terms of resilient modulus, TSR and moisture resistance properties. M4.2 specimens recorded a resilient modulus and TSR value higher than of unmodified specimen M4.1 by 1252.5MPa and 0.02 respectively although stating both specimens have adequate TSR values. It was further proposed that the inclusion of cement produced specimens less susceptible to moisture damage as to when compared to control specimens. Alternatively, a negative correlation was observed between the amount of modifier used within P3 specimens and the resilient modulus value recorded. A drop of 2125MPa was seen between specimen P3.1 using 0% modifier against specimen P3.4 produced with 30% modifier in terms of resilient modulus values.

Similar resilient modulus figures were noted between unmodified specimens M4.1 and P3.1 recording 2556MPa and 2625MPa however, a completely different story is told when comparing their modified counterparts. While the modified specimen M4.2 recorded a resilient modulus of 3808.5MPa, the highest resilient modulus recorded by specimens produced with the variants of emulsion P3 was 736MPa by specimen P3.2, a decrease by 3072.5MPa. Both specimens produced by the variants of emulsion B1 and C1 noted having high void contents and in theory, as said by the specimens produced with emulsion C1.1 and C1.2, the specimens may most likely suffer moisture induced deterioration however, the test roads produced by emulsions B1.1 and B1.2 observed no signs of frost cracking corelating to other specimens mentioned in Table 11 having good moisture resistant characteristics. Moreover, the TSR values of modified specimens outperformed their unmodified counterparts as seen in the specimens produced with the variants of emulsion M3 and M4 hence having improved resistance to moisture. While the modified specimen M3.4 recorded a TSR value higher by 0.09 than of the modified M4.2 specimen, specimen M4.2 outclassed modified specimens M3.3 and M3.2 by 0.09 and 0.04 respectively.

As for the cement modified specimens M6.2 and M6.3, lower air void contents could be achieved under specific curing conditions which causes the specimens to be less susceptible to moisture induced damage. Furthermore, by the use of the double compaction method and the increase in compaction blow frequency, air voids again can be significantly reduced which in turn improves the water-resistant properties of cold mix asphalt specimens.

Similar to M6.2 and M6.3 specimens, the cement-modified specimens from the variants of emulsion M7 noted an improvement in moisture susceptibility resistance due to the cement drastically decreasing the moisture loss rate.

ID	properties	summary	
B1(1-2)	Void content, frost cracking	• Despite the high void content in the test roads, no signs of frost cracking were observed	
C1(1-2)	Stripping and moisture resistance, void content	• Rapid-hardening cements consume plenty water hence may lower the stripping and moisture damage potential of specimens • Large amount of air voids hence specimens may suffer from moisture induced deterioration	
M3-1	Tensile strength ratio (TSR), moisture resistance	TSR: 0.33	M3.1 had a poor TSR while modified specimens M3.2, M3.3 and M3.4 had adequate TSR values hence having an improved resistance to moisture
M3-2		TSR: 0.86	
M3-3		TSR: 0.81	
M3-4		TSR: 0.99	
M4-1	Resilient modulus, TSR value, moisture resistance	• highest resilient modulus value recorded was 2556MPa • recorded an adequate TSR value of 0.88	
M4-2		• highest resilient modulus value recorded was 3808.5MPa • recorded an adequate TSR value of 0.90 • The inclusion of cement makes specimens less susceptible to moisture damage when compared to control specimens	
P3-1	Resilient modulus (RM)	Average RM: 2625MPa	• Negative correlation between the modifier Used Cylinder Oil (UCO) content and the RM values of specimens
P3-2		Average RM: 736MPa	
P3-3		Average RM: 550MPa	
P3-4		Average RM: 500MPa	
M6-1	Void content	-	Increasing the number of compaction blows and using the double compaction method significantly reduces the void content of specimens hence improving their water-resistant properties
M6-2		• Specimens with a low cement content can obtain a lower air void content when under the single-curing condition hence less susceptible to moisture induced damage	
M6-3		• Specimens with a high cement content can reach a lower air void content when under the mixed-curing condition hence less susceptible to moisture induced damage	
P7(1-2)	Microcracks initiation	• Specimens produced with the polymer-modified emulsion P7-2 can postpone the microcracks initiation by a further 1900 cycles in comparison to P7-1 specimens hence having better resistance to water induced damage	
M7(1-4)	Moisture loss rate, moisture susceptibility resistance	• Modifying specimens with Cement significantly decreased moisture loss rate while improving moisture susceptibility resistance	
P8	Water stability	• P8 specimens, being made with SBS modified bitumen emulsion, had comparable water stability performances to hot and warm mix asphalt specimens	

Table 11: Water resistant properties of cold mix asphalts

Specimens produced with polymer-modified emulsions P7.2 and P8 both observed positive outcomes. While specimens produced with emulsion P7.2 stated having a better resistance to water induced damage through the postpone of microcrack initiation, being an additional 1900 cycles higher than of its unmodified counterpart P7.1, P8 specimens made known that its specimens had water stability characteristics comparable to that of hot and warm mix asphalt.

5.2 RESISTANCE AGAINST AGEING

The studies stated within table 12, 13 and 14 investigate the ageing characteristic of cold asphalt pavements over a period of time. Independent variables such as the type of emulsion or modifier used were also investigated to assess their effect on the long-term performance of cold mix asphalt pavements. Such properties are desired to reduce service life costs on maintenance or having to replace a section of road completely due to its poor ageing characteristics hence reaching the end of its service life. An overlooked issue on increased maintenance works due to a poor mixture of cold mix asphalt being used to lay section of road are the delays and road diversions which in turn increase both noise and air pollution. Changes were observed in parameters including the void content percentage, stiffness modulus and indirect tensile strength values during the pavement's service life or over time while being studied in a lab, all of which mostly proved to show adequate long-term performances. Clear correlations and patterns were displayed between such key parameters and either their service or curing time all of which are stated in the performance column.

In general, the void content and penetration depth of B1.1 and B1.2 specimens decreased with time unlike the specimens produced with the variants of B3 where void content increased with time. Overall, B1.1 specimens recorded lower void contents than its counterpart B1.2 while having higher indirect tensile test and stiffness modulus values. The void contents observed on specimens B1.1 and B1.2 were lower than the specimens produced with the variants of emulsion B3 despite being tested over a longer time period. Although the specimens produced with the variants of emulsion B3 outperformed specimens made with emulsion B1, both noted a positive correlation between IDT figures and time. Similar patterns were observed with stiffness modulus figures having a positive correlation with time however, with specimens B1.1 and B1.2 significantly outclassing the specimens produced with the variants of emulsion B3 which may be due to their curing time and years in service. It was also made known that the lower the penetration grade, the lower the void content as seen in the specimens produced with the variants of emulsion B3.

Both specimen B7 and specimens of the variants of M1 recorded positive correlations between time and stiffness modulus values as seen in other specimens however, B7 specimens performed exceptionally well recording higher values than of specimens produced with emulsion B1.1 and B1.2 despite having a shorter curing time. After 56, 230 and 508 days of curing, specimen B7 recorded ITSM values ranging from approximately 3500MPa to 4400MPa, 4900MPa to 6100MPa and lastly 5500MPa to 6200MPa respectively. While unmodified specimens observed adequate deformation characteristics, reporting aspects such as no noticeable rutting or frost damage being observed over long time periods, the modified specimens included in table 13 and 14 tell two different stories. The modified specimens seen in P6 and the variants of emulsion M3 had better resistance to permanent deformation than of unmodified specimens however, the inclusion of the polymer in specimens P3.2, P3.3 and P3.4 caused inadequate permanent deformation micro-strains compared to unmodified specimen P3.1 having an adequate permanent deformation. The strain of modified specimens P3.2, P3.3 and P3.4 undesirably continued to increase with time unlike the unmodified specimen P3.1. Further parameters such as bulk densities and wear resistances of specimens were assessed. Specimens produced with the variants of emulsion B3 demonstrated a negative correlation between bulk density and time. While specimen B3.2 recorded the highest bulk densities at any given time, it was observed that after 28 days of curing, there were minimal changes in bulk density and when a specimen is produced with a lower penetration grade bitumen emulsion, the bulk density of specimens would increase.

<table>
<tr><th>ID</th><th>Property</th><th colspan="3">Performance</th></tr>
<tr><td rowspan="3">B1-1</td><td rowspan="6">Void content (VC), Indirect Tensile test (IDT), Stiffness modulus (SM), penetration (Pen) and softening point (SP)</td><td>Yr 0</td><td>VC: 10.4%, IDT: 325kPa, SM: 1450MPa, Pen: 160/220
SP: 39°C</td><td rowspan="6">Negative correlation between time and both void content and penetration depth

Positive correlation between time and IDT, SM and SP values

Performed well over 14 years in service as a wearing course
No noticeable rutting observed
Good stability and durability
No frost damaged</td></tr>
<tr><td>Yr 2</td><td>VC: 9.1%,
IDT: 400kPa, SM: 2700MPa, Pen: 148mm
SP: 40°C</td></tr>
<tr><td>Yr 5</td><td>VC: 10.3%, IDT: 764kPa, SM: 4646MPa, Pen: 114mm
SP: 42°C</td></tr>
<tr><td rowspan="3">B1-2</td><td>Yr 0</td><td>VC: 12.4%, IDT: 185kPa, SM: 750MPa, Pen: 330/430
SP: 33°C</td></tr>
<tr><td>Yr 2</td><td>VC: 12.1%,
IDT: 290kPa, SM: 1450MPa, Pen: 240mm
SP: 34.2°C</td></tr>
<tr><td>Yr 5</td><td>VC: 11.3%, IDT: 507kPa, SM: 1736MPa, Pen: 178mm
SP: 38°C</td></tr>
</table>

		Yr 13	VC: 11.1% IDT: 313kPa, Pen: 175mm SP: 37.4°C	
B3(1-4)	Bulk density	After 7 days of curing, specimens produced with 11% of B3.2, B3.3 and B3.4 emulsions recorded bulk densities of approximately 2024g/cm^3, 1985g/cm^3 and 1950g/cm^3 respectively		Negative correlation between bulk density and time B3.2 recorded the highest bulk densities over time After 28 days of curing, minimal changes in bulk density are observed The lower the penetration grade, the higher the bulk density
		After 28 days of curing, specimens produced with 11% of B3.2, B3.3 and B3.4 emulsions recorded bulk densities of 2017g/cm3˒ 1970g/cm^3 and 1942g/cam^p correspondingly		
		After 84 days of curing, specimens produced with 11% of B3.2, B3.3 and B3.4 emulsions recorded bulk densities of around 2003g/cm^{3,} 1952g/cm^3 and 1941g/cm^3 separately		
	Void content	After 7 days of curing, specimens produced with 11% of emulsion B3.2, B3.3 and B3.4 recorded void contents of approximately 12.5%, 14.1% and 15.7% respectively		Positive correlation between void content percentage and time The lower the penetration grade, the lower the void content
		After 28 days of curing, specimens produced with 11% of B3.2, B3.3 and B3.4 emulsions recorded void contents of 14.1%, 16% and 17.1% correspondingly		
		After 84 days of curing, specimens produced with 11% of B3.2, B3.3 and B3.4 emulsions recorded void contents of around 14.5%, 16.8% and 17.1% separately		
	Indirect tensile test (IDT)	After 7 days of curing, specimens produced with 11% of B3.2, B3.3 and B3.4 emulsions recorded IDT values of approximately 0.49MPa, 0.52MPa and 0.35MPa respectively		Positive correlation between indirect tensile strength and time In general, the lower the penetration grade, the higher the IDT value
		After 28 days of curing, specimens produced with 11% of B3.2, B3.3 and B3.4 emulsions recorded IDT values of roughly 1.15MPa, 0.86MPa and 0.55MPa correspondingly		
		After 84 days of curing, specimens produced with 11% of B3.2, B3.3 and B3.4 emulsions recorded IDT values of 1.3MPa, 1.16MPa and 0.82MPa separately		
	Failure strain	After 7 days of curing, specimens produced with 11% of B3.2, B3.3 and B3.4 emulsions recorded failure strains of approximately 13.9%, 15% and 16.6% respectively		Negative correlation between failure strain percentage and time The higher the penetration grade used, the higher the failure strain
		After 28 days of curing, specimens produced with 11% of B3.2, B3.3 and B3.4 emulsions recorded failure strains of roughly 8.4%, 9% and 11.8% correspondingly		
		After 84 days of curing, specimens produced with 11% of B3.2, B3.3 and B3.4 emulsions recorded failure strains of around 4.2%, 6.4% and 7.2% separately		
	Stiffness modulus	After 7 days of curing, specimens produced with 11% of B3.2, B3.3 and B3.4 emulsions recorded stiffness modulus values of approximately 300MPa, 325MPa and 225MPa respectively		Positive correlation between stiffness modulus values and time Emulsion B3.3 outperformed its counterparts
		After 28 days of curing, specimens produced with 11% of B3.2, B3.3 and B3.4 emulsions recorded stiffness modulus values of roughly 820MPa, 870MPa and 640MPa correspondingly		
		After 84 days of curing, specimens produced with 11% of B3.2, B3.3 and B3.4 emulsions recorded stiffness modulus values of around 1420MPa, 1580MPa and 1120MPa separately		

B7	Indirect tensile stiffness modulus (ITSM), deformation resistance	Positive correlation between ITSM value and days of curing at between 5°C and 10°C After 56, 230 and 508 days of curing, specimens recorded ITSM values ranging from approximately 3500MPa to 4400MPa, 4900MPa to 6100MPa and lastly 5500MPa to 6200MPa respectively Long term stiffness development stabilised at 6000MPa at 10°C Site cores showed excellent deformation resistance No signs of distress after nearly 10 years having theoretical traffic count of over 10 million equivalent standard (80kn) axel loads

Table 12: Unmodified cold mix asphalt ageing characteristics

ID	Property	Performance
P3(1-4)	Permanent deformation	Although specimen P3.2 performed better than its modified counterparts, all the modified specimens P3.2, P3.3 and P3.4 recorded inadequate permanent deformation micro-strains compared to unmodified specimen P3.1 having an adequate permanent deformation After 2000 seconds, specimens P3.1, P3.2, P3.3 and P3.4 recorded permanent deformation micro-strains of roughly 6000, 15000, 17500 and 24000 respectively The strain of modified specimens undesirably continued to increase with time unlike the unmodified specimen P3.1
P6	Shear resistance, Wear resistance	Shear resistance of polymer modified specimens is roughly two times larger than of unmodified specimens Shear resistance decreases with time hence deformation increases with time After 30, 60 and 120 minutes, modified specimen P6 recorded deformation values of roughly 0.5mm, 4.2mm and 15mm respectively before breaking while the unmodified specimen broke after 60 minutes with a high deformation of 20mm Positive correlation between wear percentage and time Modified specimens have a higher wear resistance than of unmodified specimens After 15, 35 and 50 minutes, P6 specimens recorded a wear percentage of approximately 0.2%, 2% and 8% correspondingly while unmodified specimens recorded wear percentages of roughly 5.6%, 9.8% and 14% after 5, 10 and 15 minutes separately

Table 13: Polymer cold mix asphalt ageing characteristics

ID	Property	Performance
M1(1-3)	Indirect tensile stiffness modulus (ITSM), ITS (indirect tensile strength), permanent deformation, Axial strain %	Positive correlation between curing time and ITSM, ITS Cement modified specimens had better resistance to permanent deformation as well as both ITSM and ITS values than unmodified specimens Unmodified specimens recorded ITS values of 198kPa and 315kPa after 3 and 28 days of curing respectively Cement modified specimens recoded ITS values of 327kPa and 512kPa after 3 and 28 days of curing Cement modified specimens recorded lower axial strain percentages than of unmodified specimens After curing at 20°C for 28 days, fully wrapped unmodified and cement modified specimens recorded axial strain percentages of roughly 0.62% and 0.5% respectively after 1000 pulses

Table 14: Mixed modified cold mix asphalt ageing characteristics

CONCLUSIONS

To conclude, the following observations were made regarding the findings within the state of art review paper concerning bitumen emulsions, the use of modifiers and their effect within cold mix asphalt. Below, Table 15 is the key to Table 16 which displays the overall effects of different modifiers on a variety of cold mix asphalt properties in terms of being improved or worsened.

Cationic bitumen emulsions are the popular choice of charge for use within mixtures whilst the most common grade of bitumen emulsion was revealed to be 160/220, being numerously referenced within the review paper. The majority of bitumen emulsions were recorded having bitumen contents of 60% while the other bitumen emulsions recorded percentages which spanned from 57.2% to 70%, thus not too far off from the common 60%. A predictable positive correlation is detected between the penetration grade of unmodified bitumen emulsions and their penetration depth as was seen with the variants of emulsion B3 with emulsion B1.2 being an anomaly.

The addition of polymers including the amount added effects the overall physical properties of a bitumen emulsion such as its penetration depth, softening point and flash point temperatures as seen in the variants of emulsion P3. Generally, negative correlations are observed between the penetration grade of unmodified bitumen emulsions and their viscosity, softening point and flash point although the addition of various additives and modifiers can affect such properties. Concerning the cement modified emulsion C1.1 and C1.2, it is crucial to state that the use of a cationic emulsion goes in conjunction with a rapid-setting emulsifier and an anionic emulsion goes in conjunction with a slow-setting emulsifier when modifying an emulsion with cement. A range of different aggregates were used within different mixtures such as granite, limestone and various types of sand despite limestone being the popular choice of aggregate or filler. In terms of gradations, modified cold mix asphalt mixtures sought after dense gradations.

Indisputably, the surface properties of an asphalt specimen can easily be influenced by a broad range of factors including both the constituent materials used and the external factors of specimens such as their curing condition. The addition of cement positively influences both the skid resistance and texture depth of cold mix asphalt specimens regardless of being tested in wet or dry conditions. As expected, cold mix asphalt specimens recorded higher pendulum test values in dry conditions than of wet. The modifier used in emulsion P6 positively improved drainage properties and provided reductions in the glare of cold mix asphalt specimens. The addition of some modifiers such as used in emulsions M2.2 and P6 can both positively enhanced the functional properties of cold mix asphalt specimens to the point where it exceeds that of hot mix asphalt specimens at particular speeds.

A good range of factors can affect the moisture susceptibility of an asphalt pavement ranging from the constituent materials used within its mixture to the external factors such as their curing condition. Unmodified cold mix asphalt specimens produced with the variants of emulsion B1 observed no frost cracking in their test roads over a period of years despite having a high void content which again goes against popular belief that high air void content specimens are more susceptible to moisture induced damage. The addition of modifiers such as ordinary Portland cement positively influenced both the moisture susceptibility resistance of cold mix asphalt specimens whist the SBS-polymer modified specimens showed to have comparable water stability properties to that of hot and warm mix asphalt.

The addition of rapid-hardening cements, as used within C1 emulsions, can result in a reduction in the stripping and moisture damage potential of specimens however noting a large quantity of air voids hence may increase a specimen's susceptibility to moisture induced deterioration. The inclusion of UCO modifier proved to be detrimental to the water resistance of specimens stating a negative correlation between the modifier content and the resilient modulus value. It can then be stated that the addition of modifiers, excluding that from the variants of emulsion P3, positively influenced the moisture susceptibility of cold mix asphalt specimens, performing better than of unmodified specimens, despite increasing their air void content in some instances.

In general, the cold mix asphalt specimens mentioned within the review paper displayed good mechanical performances including water resistance and ageing characteristics, whether being modified or unmodified, although the modified specimens outperformed unmodified specimens. A negative correlation is observed between the grade of bitumen emulsion used and the mechanical performance of cold mix asphalt, more specifically the creep stiffness and complex shear modulus. Some specimens mentioned reported good aging characteristic such as observing minimal cracks and no noticeable rutting while having good durability and resistance to low temperature cracking.

It was then proposed that under specific curing conditions, compaction blow frequencies and compaction methods, a significant reduction in specimen's air void content can be achieved hence creating specimens less susceptible to moisture induced damage and with the use of certain modifiers, such as used in emulsion P8, specimens can achieve water stability characteristics comparable to hot and warm mix asphalt specimens.

Adequate or exceptionally well deformation characteristics were observed by both modified and unmodified specimens, contrary to the popular belief that cold mix asphalt has poor aging characteristics. Positive correlations were observed between time and stiffness modulus values with some specimens reported having adequate deformation characteristics, observing no noticeable rutting or frost damage over long time periods. Modifiers used in specimens P6 and the variants of M3 each performed better than of the unmodified specimens in terms of their resistance to permanent deformation however, the modifier used in P3 specimens proved to be detrimental, causing inadequate permanent deformation micro-strains.

Key	
Improved	↑ (green up arrow)
Adequate/No Change	→ (yellow arrow)
Worsened	↓ (red down arrow)
NA	→ (grey arrow)

Table 15: Key to Table 16

ID	Modifier	Mechanical		Functional		Long-term	
		Strength	Stiffness	Texture	Skid Resistance	Water Resistance	Ageing Resistance
P2.2	Polyvinyl Acetate	Improved	Improved	NA	NA	NA	NA
P3(2-4)	Used Cylinder Oil	Worsened	Worsened	NA	NA	Worsened	Worsened
P6	Polyacrylonitrile, ethylene vinyl acetate polymer	Improved	Improved	Improved	Improved	NA	Improved
P7.2	Polymer	Improved	Improved	NA	NA	Improved	NA
P8	SBS polymer	Improved	Improved	NA	NA	Improved	NA
C1(1-2)	Rapid-hardening Cement	Improved	Improved	NA	NA	Adequate/No Change	NA
M1(2-3)	Cement	Improved	Improved	NA	NA	NA	Improved
M2.2	Cement	Worsened	Worsened	Improved	Improved	NA	NA
M3.2	Unspecified modifier	Worsened	Adequate/No Change	NA	NA	Improved	NA
M3(3-4)	Cement	Improved	Adequate/No Change	NA	NA	Improved	NA
M4.2	Cement	Improved	Improved	NA	NA	Improved	NA
M6(2-3)	Cement	Improved	Improved	NA	NA	Improved	NA
M7(2-4)	Cement	Improved	Improved	NA	NA	Improved	NA

Table 16: General effects of modifiers on mechanical, functional and long-term properties of cold mix asphalt specimens

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