IOP Conference Series: Earth and Environmental Science

Durability of POFA-modified dense-graded cold mix asphalt

To cite this article: K R Usman *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **971** 012006

IOP Conf. Series: Earth and Environmental Science **971** (2022) 012006 doi:10.1088/1755-1315/971/1/012006

Durability of POFA-modified dense-graded cold mix asphalt

K R Usman[1,3], M R Hainin[1,2*], M K I M Satar[1], M N M Warid[1], M A Bilema[4], A Usman[5] and A J Zulfiqar[1,6]

[1]School of Civil Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia.
[2]Department of Civil Engineering, College of Engineering, University Malaysia Pahang, 26600 Pekan, Pahang, Malaysia
[3] Department of Civil Engineering Technology, School of Engineering Technology, Nuhu Bamalli Polytechnic Zaria, P.M.B 1016, Zaria, Kaduna State, Nigeria.
[4]Department of Civil Engineering, Faculty of Engineering, Benghazi University, Benghazi, Libya.
[5]Civil and Environmental Engineering Department, Universiti Technologi PETRONAS, Bandar Seri Iskandar, Perak, 32610, Malaysia.
[6]Department of Civil Engineering, Balochistan University of Engineering and Technology, Khuzdar, Pakistan.
*Corresponding author: mrosli@utm.my

Abstract. Cold mix asphalt (CMA) is a versatile and energy efficient mixture often prepared at ambient temperature. Efforts to improve the performance of CMA mixtures recorded appreciable success. Nonetheless, the critical performance measures of moisture and abrasive resistance still baffles researchers. Additionally, CMA's design, production, testing, and site application is bedevilled by slow rate of strength gain, high void content, and absence of a globally acceptable mix design. This study aimed at assessing CMA's durability measures using the modified Lottman (moisture damage) and Cantabro tests by adding a 3% palm oil fuel ash (POFA) as filler replacement and 3% cement. Fast-curing mixtures fabricated with a cationic quick-set (CQS-1h) and a rapid-set (RS-1K) emulsion both of medium viscosities with a nominal maximum aggregate size (NMAS) of 4.75 mm were evaluated. In addition to improving the Marshall volumetric properties, POFA's inclusion is aimed at improving adhesion thereby enhancing the durability of the fine dense-graded cold mix asphalt (FGCMA-4.75 mm). The modified Marshall as stated in the asphalt institute (AI) manual series (MS-19) for dense-graded CMA was used for design. Results indicated that POFA reduces the void, improves stability, and enhance durability. Moreover, the CQS-1h has better durability for both control (FGCMA-C) and POFA-modified mixtures (FGCMA-P). While RS-1K has higher tensile strength in both dry and moisture-conditioned states with a higher tensile strength ratio (TSR) for both FGCMA-C and FGCMA-P mixtures. POFA's pozzolanic capability proves effective in improving the durability and moisture damage resistance of FGCMA-P.

1. Introduction

Asphalt mixtures for pavement construction, rehabilitation and maintenance are mainly produced as Hot Mix Asphalt (HMA) in most part of the globe for its durability, and safe riding quality. However, release of greenhouse gases, other harmful fumes, and influence of weather on mixing and laying encourages exploring of viable alternatives to HMA by stakeholders, especially researchers [1,2]. The recent global sustainability campaign aimed at curbing the negative effect of global warming, eschew unhealthy environmental practices, and minimise the use of non-renewable resources led to the introduction of low-temperature paving technologies in form of warm mix asphalt (WMA) [3]. WMA can save up to 70% energy when compared to a conventional HMA, and its performance is often reported to be superior than that of HMA, but WMA additives are costly while its production needs skill and heating too [4]. Other low-temperature paving mixtures include half-warm mix, and semi-warm mix asphalt. The mixing temperature requirement for WMA between 100 – 140 °C still emits harmful fumes affecting both the atmosphere and the workers alike with attendant handling difficulty [2]. Consequently, cold mix asphalt (CMA) promises to be a better alternative mixture to both HMA and WMA since it is produced without heating, thus releases zero fumes.

CMA has gained recognition in recent years for its superior energy saving, zero fumes emission, ease of production, minimal equipment and skill requirement. CMA is produced from a mixture of well-graded aggregates, water, emulsified asphalt, and additives mixed and placed at a temperature in the range of 0 – 60 °C, but mostly at ambient temperature [5]. Its versatility made it applicable in subbases, base courses and wearing courses of pavements as new construction and as a maintenance mixture for medium to heavy-trafficked roads [6,7]. However, challenges associated with CMA of slow strength development rate, and weak early strength has relegated the use of CMA to maintenance works. Furthermore, other most critical challenges inhibiting CMA's use include high susceptibility to moisture damage due to its inherent high voids and low abrasion resistance due to its peculiar lower base binder content.

Several efforts by researchers were made to solve the aforementioned challenges especially, the moisture resistance of CMA. The typical method, which was developed by Hughes and adapted with minor modifications by the Asphalt Institute (AI) requires measuring the tensile strength of wet CMA specimens subjected to three (3) hours vacuum saturation at room temperature in comparison to the tensile strength of the dry samples [8]. Boiling test and Coating ratio are the two related common tests utilised for testing CMA's and warm mix asphalt's moisture damage resistance [9,10]. However, coating test does not truly mimic site in-service conditions and because these tests are conducted on the component materials, some aggregates may perform worse in those tests individually, but do great in a mixture. This could be explained by the interaction of the aggregate's chemical component with other materials in a mixture [11].

Therefore, this study set to test moisture damage in CMA by subjecting samples to the same 60 °C total water immersion for 24 hours similar to that for HMA to simulate worst case scenario. On the other hand, the solutions proffered towards improving CMA abrasion resistance include the inclusion of pozzolanic fillers to which POFA belongs. These pozzolanic fillers of either biomass or industrial origins and notably rich in calcareous and siliceous bases improves CMA performance [12]. The use of pozzolanic fillers serves a dual purpose of reducing void and improving mixture's adhesion. POFA is a dark-grey ash by-product obtained by burning parts of a palm tree. A recent study by the author revealed that the addition of 3% POFA (0.075mm size) by aggregate weight is effective in improving the mechanical performance of dense-graded CMA [7]. Moreover, POFA's inclusion in CMA will ameliorate environmental hazards posed by its landfill disposal whilst upholding sustainable engineering practice.

2. Materials and test methods

The detailed properties of the materials used in this study and the methodology employed are explained in section 2.1 to 2.5.2.

2.1. Binders

Two categories of binders are used for this study namely; primary and secondary binders. The primary binders are the emulsified asphalts while the secondary binder is the cement.

2.1.1. Emulsified Asphalt. Emulsified asphalt is a homogenous mixture of an oil-based and water-based liquids. The two liquids are dispersed into tiny globules held in position by differing electrical charges with the help of a 'SURFace ACTion AgeNT' (Surfactant). Depending on the category of the emulsion, the surfactant also imparts the setting characteristics of the emulsion, either rapid, slow, medium, or quick setting. The higher the concentration of the charges around the bitumen droplets, the slower will be the setting rate. Emulsion viscosities are designed to enable low temperatures application as cold mixtures are mostly applied in slurry form [13]. Traditionally, medium to slow setting emulsions is often used for CMA production to allow for ample time for mixing and placing on site. However, to solve the lingering challenge of slow strength development a quick and rapid set cationic emulsions are introduced in this study.

Cationic emulsions are compatible with both alkaline and acid-nature aggregates which ensures greater adhesion and aggregate stone-on-stone lock [14]. The durability of CMA is dependent on the emulsion performance which is translated by the film-thickness on the aggregate. But the asphalt film thickness on the aggregate relies on the amount of water and breaking speed of the emulsion. Thus, the addition of prewetting water during CMA mixing hampers adequate adhesion and proper coating, hence exclusion of prewet water is considered in this study. Enhanced adhesion reduces the high void content peculiar with CMA, and a reduced void improves the moisture damage resistance component of CMA's durability [15]. Moreover, the durability performance of dense-graded CMA is more compared to other gradations, nonetheless, the samples preparation and testing for moisture damage test differs [16]. The emulsion types used are a quick and a rapid set emulsion both of medium viscosities.

The quick set emulsion is polymer-modified cationic (CQS-1h) emulsion specifically meant for emulsified asphalt slurry seals, allowing faster curing of the mixture and early opening to traffic. Both emulsions were tested of mechanical performance whilst their residues further evaluated for rheological behaviour. Conditioning of emulsions before each test was done at 25 ºC according to ASTM D244 while adjustments were made where necessary to replicate on-site service conditions as reported by Usman [18]. In a nut shell, quick and rapid set emulsions is pertinent towards early opening of the road to traffic, especially in the absence of solar radiation, and low humidity [19].

Table 1 present the result of the emulsions and their residues' tests in accordance to the American Society for Testing and Materials (ASTM) and American Association of State Highway and Transport Officials (AASHTO). The result revealed that the requirements set by Jabatan Kerja Raya (JKR) – Malaysian Public Works Department for cold mixes were satisfied [20].

Table 1. Physical and mechanical properties of RS-1K and CQS-1h.

TEST ON EMULSIFIED ASPHALT						
Test Description	Test Method		Result		Specification (CQS/RS)	Requirement
	AASHTO	ASTM	RS-1K	CQS-1h		
Physical appearance	-	-	brownish	brownish		
Storage stability (%)	T 59	D6930	1.0	0.9	1% max.	
Settlement test (%)	T 59	D6930	1.0	1.0	1% max.	JKR, 2008, MS 161, & ASTM D2397
Residue by evaporation (%)	T 59	D 6934	63	65	57/50 min.	
Particle charge	-	D 7402	Positive	positive		
Saybolt Furol viscosity (Sec)	-	D 7496	22	20	15 – 50	
TEST ON EMULSIFIED ASPHALT RESIDUE						
Penetration at 25 ºC (0.1 mm)	D5	T 49	40	68	40/60 – 90/200	
Softening point (ºC)	D36	T 53	69	-	54 – 57ºC min	JKR
Solubility in Trichloroethylene (%)	D2042	-	95	100	97.5 min	

2.1.2. Cement. An ordinary Portland cement conforming to ASTM C150/C 150M - 11 was used as part of the aggregate gradation. It is added as a supplementary binding agent in CMA mixtures [21]. Usually, 1-2% by aggregate weight is added to a CMA mixtures [22,23]. A crucial role of cement in

IOP Conf. Series: Earth and Environmental Science **971** (2022) 012006 doi:10.1088/1755-1315/971/1/012006

this study was to trigger the cementitious properties of the POFA, which is a pozzolana, and pozzolanas only contribute their cementing or binding properties in the presence of SiO_2 (lime) which provided by cement [24]. In addition to the dual role of binding aggregate and supplementing pozzolanic reactivity, cement do assist in the early strength development and curing (water expulsion) of CMA by heat of hydration. For this study, a fixed 3% cement by total weight of aggregate was used for the control and POFA-modified mixtures alike. The cement was mixed with the aggregate dry and subsequently added to the emulsified asphalt.

2.2. Granite Aggregate

The aggregate for this study was dried at a temperature of 110 ºC in the oven and sieved according to the various sizes in the gradation. The choice for granite aggregate was in consonance to the fact that it is an acidic nature aggregate. Acidic aggregates were reported to be compatible with cationic emulsions, and most preferred than anionic emulsions in terms of enhanced adhesion [14].

The aggregate's mechanical performance was tested according to specified standards and result presented in Table 2.

The result in Table 2 indicated that the aggregate has a negligible water absorption, hence, the decision to eliminate addition of premix water did not affect the mix's performance. The aggregate also has a high angularity well above the minimum limit of 45% in addition to an excellent abrasion resistance. The absence of deleterious substances is key to proper aggregate-binder bonding in CMA, the sand equivalent result revealed that the aggregate of being free of clay and other organic particles capable of reducing bonding.

Table 2. Mechanical Properties of fine and Coarse aggregate.

Aggregate	Properties		Granite	Limit	Relevant Specification
Fine aggregate (< 4.75mm)	Specific Gravity	-	2.89	-	ASTM C 128
	Sand Equivalent	(%)	96.0	> 45	ASTM D 2419
	Water Absorption	(%)	0.48	< 2	ASTM C 128/MS 30
Coarse aggregate (> 4.75mm)	Bulk Density	(Kg/m^3)	1815	-	ASTM C 128
	Fine aggregate angularity (FAA)	(%)	54.13	> 45 %	ASTM C 1252
	Los Angeles abrasion value (LAAV)	(%)	23.00	< 45 %	ASTM C131/AASHTO T96
	Flakiness Index	(%)	17.40	< 20	BS 812-21:1989

The plot of the aggregate gradation used in this study with a nominal maximum aggregate size of 4.75 mm is presented in Figure 1.

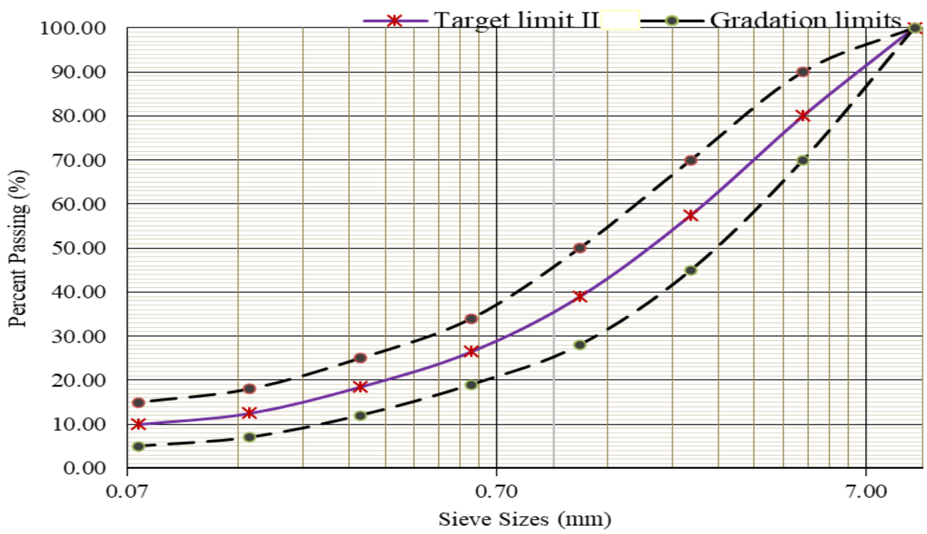

Figure 1. Aggregate Gradation for CMA.

2.3. Palm oil fuel ash

Palm oil fuel ash (POFA) is used in this study as a cementitious pozzolanic material that aid CMA adhesion. It is a by-product obtained by burning palm tree biomass, including empty palm fruit bunches, kernels/shells, fibres, fronds, and palm leaves in palm oil mills, and power generating plants. POFA is typically grey but turns black when the proportion of unburnt carbon becomes high. The black POFA reverts grey by further burning the black POFA at 1000°C. Aside of fly ash, POFA was opined as the second most attractive filler used for construction [25]. POFA is inert however, in the presence of water act as a pozzolana in construction, especially, concrete in which it acts as a supplementary cementing material with excellent flowability and anti-segregation ability [26].

Many studies had proven POFA as a pozzolanic material [27]. In asphalt concrete and bitumen modification, POFA has gained increasing attention with attendant good performance [10]. However, not much was achieved in the utilisation of POFA in asphalt concrete mixtures, especially, cold mixtures. Recently, the inclusion of POFA in CMA was studied by the author and 3% by aggregate weight in a fine dense-graded aggregate matrix was discovered to yield optimal performance [7]. The chemical composition of POFA as revealed by a number of researches signifies that it contains cementitious chemical compounds like silica, alumina, and oxides of magnesium, iron and calcium [27]. The chemical properties of POFA as reported by various researchers is presented in Table 3.

Table 3. Chemical Properties of POFA reported in the literature.

Percentage Chemical Constituent	Researchers											
(%)	[28]	[29]	[30]	[31]	[7]	[32]	[33]	[34]	[35]	[36]	[37]	[38]
SiO_2	65.01	43.60	65.30	64.17	62.60	55.20	71.67	59.62	79.31	63.41	55.50	64.20
Al_2O_3	5.72	11.40	2.50	3.73	4.65	4.48	0.94	2.54	3.15	5.55	9.20	4.25
Fe_2O_3	4.41	4.70	1.90	6.33	8.12	5.44	2.77	5.02	7.12	4.19	5.60	3.13
CaO	8.19	8.40	6.40	5.80	5.70	4.12	5.61	4.92	2.79	4.34	12.40	10.20
MgO	4.58	4.80	3.00	4.87	3.52	2.25	4.91	4.52	1.21	3.74	4.60	5.90
K_2O	6.48	3.50	5.70	8.25	9.02	2.28	7.89	7.52	3.23	6.33	-	8.64
SO_3	0.33	2.80	0.40	0.72	1.16	2.25	1.03	1.28	0.45	0.91	2.30	-
MnO	0.11	-	-	-	-	-	0.12	-	-	0.17	-	-

P_2O_5	4.69	-	-	5.18	-	-	-	3.58	2.32	3.78	-	-
Na_2O	0.07	0.39	0.30	0.18	-	0.10	0.12	0.76	-	0.16	-	0.10
TiO_2	0.25	-	-	-	-	-	0.09	-	-	0.33	-	0.09
C	0.09	-	-	-	-	-	-	-	-	-	-	-
SiO_2 $+Al_2O_3$ + Fe_2O_3	75.14	59.70	69.70	74.24	75.37	76.12	95.15	67.18	89.58	92.91	70.30	96.51

From Table 3, it is glaring that all POFA samples irrespective of their origin or production parameters, has high SiO_2, Al_2O_3, and Fe_2O_3 with silicone dioxide having the highest percentage. Generally, most POFA samples satisfied to be classified as 'class F' pozzolana according to ASTM C-618 [39]. The high silicone dioxide content common with most POFA samples makes it idle pozzolanic candidate which enhances aggregate-binder bonding aided by cement hydration [38]. The incorporation of POFA in CMA will improve its early strength via increased adhesion from cement-pozzolan-water hydration which will in turn improve durability. Furthermore, the durability of CMA based on ITSR result was reported to improve significantly compared to control mixtures with the inclusion of pozzolanic ash (Fly ash and Ground Granulated Blast Furnace Slag) [40]. Furthermore, the geometric increase in crude palm production in Malaysia suggested a matching quantity of waste generation as over 1000 tons of POFA are dumped in landfills [29,41]. Incorporating POFA waste in construction will ameliorate the detrimental consequences of its landfill disposal as the waste has reached worrying levels in Malaysia [38].

2.4. Test Methods

The constituent materials were tested for compliance to relevant specifications and compatibility with each other. The mixtures are designed employing the standard Marshall design method using 75 blows and sample conditioning before testing in a water bath at 60 ºC. It is worth mentioning that the usual CMA Marshall design employs 50 blows/face and a sample conditioning at ambient temperature which ranges from 10 ºC to 40 ºC [42,43]. Absence of a universally accepted mix design led to the customisation of CMA mix design, in USA superpave approach is used while in Africa and Asian countries a modified Marshall is used [4]. The modified Marshall method based on Illinois study was used for this study and samples were further tested for moisture damage and Cantabro performance measures. Subsequent section detailed the material preparation, mixture design, and performance testing.

2.4.1. Mix Proportion and Sample Preparation. All the mixtures were prepared in accordance to the revised practice for the preparation of Marshall samples outlined in ASTM D6926-10 [44]. Regarding the gradation, CMA could be prepared with a wide-ranging aggregate gradation including dense-graded, gap-graded, open-graded, and uniformly-graded mixes. A total combined aggregate weight including filler, cement and POFA of 1000g was batched as against the usual 1200g for a standard Marshall sample. The reason was to curb the swelling effect of the mix experienced especially with the addition of premix water, and to allow for adequate compaction. Thus, premix water was eliminated because samples swell above the mould and needed to be trimmed to size. This was to ensure proper adhesion thereby increasing moisture damage resistance and improve durability, as moisture present in CMA hampers good performance [4].

The initial emulsion content (IEC) was established by employing the AI empirical formulae which depends on the gradation type base on percentages passing the 4.75 mm, 2.36 mm and 0.075mm test sieves. An IEC of 8% was obtained and varied by adding and subtracting 0.5% in two steps above and below the 8% to form an emulsion range of 7 – 9%.

The aggregate was manually mixed dry in a bowl after which the required emulsion percentage was added and further mixed to obtain a minimum of 50% coating. Emulsions were conditioned in a water bath at 25 ºC, mixed thoroughly for homogeneity before being added to the aggregate and further mixed at ambient temperature. The mixture was then transferred into pre-oiled moulds in three (3) layers. Each layer was given fifteen (15) light strokes by the mould's periphery and ten (10) blows at the centre with a 10 cm long and 5 mm wide rod, as spelt out in ASTM D6926 –10 [44].

Considering the higher void levels obtained with the standard CMA compaction level of 50 blows as specified by the Malaysia's public works department – Jabatan Kerja Raya (JKR) and India's ministry of road, transport and highways (MoRTH), adjustment were made [20,43]. This study adopted 75 blows per face for all samples in order to keep void levels to a practical minimum and to achieve maximum density. However, some researches highlighted that 3 - 5% air void is hard to achieve even at compaction levels above 75 blows [45]. Conversely, a 3 - 5% void in the total mix (VTM) was attained in a related study with the addition of 3% cement and POFA in a fine dense-graded mix. Nevertheless, concerns of aggregate crushing for coarser mixtures at higher compaction levels is imminent, yet some studies employ it but with similar or even higher void levels [42]. Unlike with other CMA mixes which collapses at early curing ages or immediately after compaction due to weak early strength, the FGCMA mix was stiff enough to withstand shocks immediately after being casted [46].

Samples were then cured in their moulds at 40 ^{o}C in an oven for 24 hours before being demoulded and subjected to a further curing at 40 ^{o}C for 72 more hours [47]. Some studies have employed similar curing procedure though at a higher temperature of 60 ^{o}C [48].

2.4.2. Mix Design. A modified Marshall design method adopted by Illinois design method as outlined in asphalt institute (AI) manual series MS-19 as elucidated in MoRTH specification was employed for designing the FGCMA-C and FGCMA-P [43]. Sample testing was done according to the revised Marshall flow and stability test contained in ASTM D6927-15 [49]. The revised test specifically suits dense-graded mixtures made from bitumen or emulsified asphalt. Additionally, theoretical maximum specific gravity of all mixtures was evaluated in accordance to ASTM D2041/D2041M – 11 [50]. Fully cured Marshall samples were evaluated for density and specific gravity measurements and subsequently transferred into a thermostatically controlled water bath set at 60 ^{o}C for forty (40) minutes prior to testing. Each of the three (3) samples for each binder content were tested one at a time by installing onto the Marshall machine mould and subjected to a gradual continuous uniform loading at a deformation rate of 50 mm/min. The Marshall stability in kilo Newton (kN) is recorded as the maximum load at failure. While the deformation in millimetre (mm) recorded by a dial gauge represents the flow of the sample.

Result of the Marshall test was plotted to obtain the optimum binder content. The determined OEC was re-confirmed by fabrication and testing samples at the established OEC. Performance testing was conducted on samples fabricated at the determined OEC as well.

2.5. Performance Testing

Durability performance tests were conducted in addition to modified Marshall test. The durability of asphalt mixtures especially, CMA is influenced by environmental conditions during their service life, whilst moisture and frost damage were identified as critical amongst other factors [39]. A similar research evaluated the durability performance of cold mix patching mixtures by employing Marshall stability, Cantabro, and wheel tracking tests [16]. Moreover, other studies employed Cantabro only for evaluating CMA durability [51]. Thus, considering the fact that moisture damage is considered a critical durability measure for CMA, utilising the modified Lottman test (moisture damage) and Cantabro test should provide adequate indication of their performance.

2.5.1 Cantabro Test. Cantabro test is considered as a cheap, fast, simple, and efficient alternative to the complex cracking durability testings for asphalt mixtures [52]. For this study, the Cantabro durability test was conducted in accordance to the Texas Department of Transportation's specification (Tx-DOT-Tex-245) or ASTM D7064 [16,53]. Notwithstanding the fact that Cantabro test was originally meant for open-graded friction courses especially at the design stage, while it is used here for production and performance assessment [53]. Cantabro test measures the resistance of the combined effect of abrasion and impact of a compacted bituminous specimen, which in turn translates to the asphalt mixture durability performance. It serves as an indication for binder-aggregate bond or adhesion properties of an asphalt mix [51].

The test was conducted by subjecting Marshall samples casted at OEC to an impact and abrasive force in a Los Angeles abrasion machine. Samples for this study were subjected to 300 revolutions in the LAAV machine at 30 rpm (revolutions per minute) without steel charges. Triplicate samples were prepared and their weights in gram (g) was measured before and after the complete revolution to the nearest whole number. The mass loss experienced by each sample is expressed as the weight difference between the final and initial weights of the sample under testing. The value expressed in percentage gives the Cantabro loss of the Marshall sample.

The percentage loss experienced by a sample represents the sample's durability; thus, the smaller the Cantabro loss, the more durable the sample is expected to be.

2.5.2. Moisture Damage Test (Modified Lottman test). This study adopted the standard HMA moisture damage protocol which involves conditioning the dry and moisture-conditioned samples in a water bath at 25 ^{o}C and 60 ^{o}C respectively with a subsequent vacuum saturation for the former. This is drastically different with the usual ambient temperature (10 – 40 ^{o}C) conditioning of CMA samples for longer duration [39]. As such the samples for dry indirect tensile strength (ITS) were conditioned at 25 ^{o}C while the moisture-conditioned samples were conditioned at 60 ^{o}C for 24 hours as in Figure 2. The air void level for all samples was kept to 7% + 1% and the durability assessment was achieved by evaluating the tensile strength ratio (TSR). The TSR is a value in percentage (%) determined by taking the ratio of the conditioned sample's ITS to those of the unconditioned samples.

The ITS test procedure for both conditioned and unconditioned samples was the same. It entails applying a constant diametral compressive force at a uniform deformation rate of 50 - 53 mm/min. The standard 101.6 mm and 63.8 mm thick samples with a nominal maximum aggregate size of 4.75 mm were loaded between the two-halves mould of a standard compression testing machine. Failure of the sample is caused by the splitting tensile stresses developed within the vertical diametric axis of each sample.

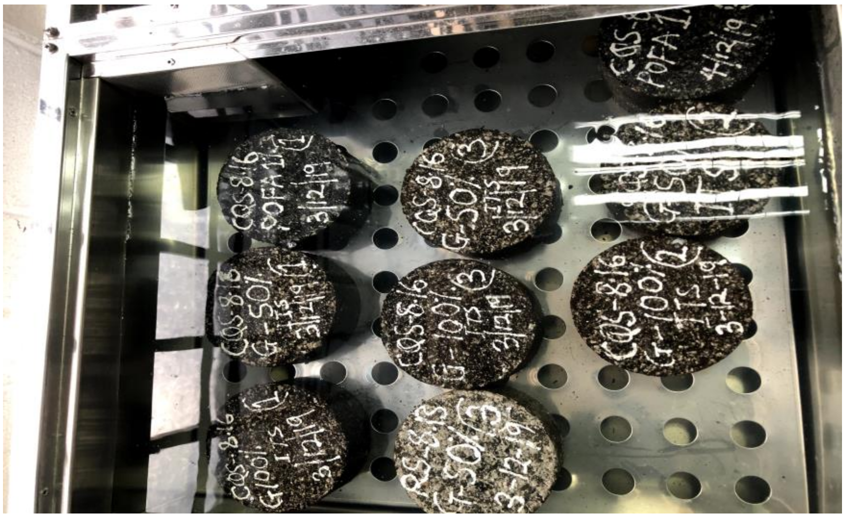

Figure 2. Moisture-conditioned samples in water bath at 60 ^{o}C.

3. Results and Discussion

3.1. Results of optimum emulsion content for the two mixtures

The optimum emulsion contents (OEC) for CQS-1h and RS-1K of the designed and control mixtures determined from Marshall testing is presented in Table 4. It is evident from Table 4 that CQS-1h has lower emulsion demand than RS-1K for both control and modified mix. This could be linked to the result of residue by evaporation in Table 1, which revealed that CQS-1h has higher base binder than do RS-1K. Therefore, as higher binder is required to coat aggregate, hence the need for higher emulsion content. The addition of POFA to the mixture has increased the emulsion demand for control and modified mixtures of both emulsions.

Table 4. Optimum emulsion contents for modified Marshall test on samples.

Percentage POFA Replacement	Mixture Designation	Average Marshall OEC (%)	
		CQS-1h	RS-1K
Control	FGCMA-C	7.7	8.1
3% POFA	FGCMA-P	8.1	8.4

The increased surface area of the POFA in the mix leads to higher emulsion absorption which in turn increases the OEC. All samples were verified for Marshall volumetric parameters at the designed OECs. Triplicate samples each for the two emulsions were casted using the established OEC and the result is presented in Table 5.

The four notable Marshall volumetric parameters of stability, flow, VTM, and voids filled with binder (VFB) were selected for all mixture types as presented in Table 5. The obtained results were compared with the MoRTH standard specifications for CMA mixtures [43]. From the values in Table 5, it is glaring that the POFA modified mixes of both emulsions have higher stability, lower voids, and higher voids filled with asphalt. Moreover, there is a significant void reduction with the addition of 3% POFA in the mixture. Equally, CQS-1h POFA-modified mixes have the highest stability of 15.35 kN as against the 13.28 kN for RS-1K. However, the lowest flow was obtained with the RS-1K emulsion for both FGCMA-C and FGCMA-P. From Table 5, tick marks were used to denote samples that passed the MoRTH requirement, while the cross marks indicate the opposite.

With the exception of the control mixtures for both emulsions, all other mixtures have satisfied the minimum criteria set by India Ministry of Road Transport and highways' (MoRTH) specifications for emulsified asphalt cold mixtures [43].

The significant void reduction achieved by POFA addition is due to enhanced adhesion achieved by the increase in hydration products from POFA's pozzolanic reaction with water and cement altogether. Similar void level was achieved with standard cold mixtures of asphalt concrete (AC) gradations and stone mastic concrete (SMA) using gyratory compactor at 40 gyrations [45].

Table 5. Summary of Marshall Verification of Result for CQS-1h and RS-1K Mixtures.

MIX TYPES	CMA MIX REQUIREMENTS & MARSHALL RESULT VERIFICATION TO MoRTH [43]							
	STABILITY (Minimum) 2.2 (kN)		FLOW (Minimum) 2.0 (mm)		VTM (Range) 3.0 - 5.0 (%)		VFB (Minimum) 15.0 (%)	
CQS-1h								
FGCMA-C	9.70	✓	2.40	✓	10.50	✗	60.20	✓
FGCMA-P	15.35	✓	2.40	✓	4.00	✓	82.40	✓
RS-1K								
FGCMA-C	10.60	✓	2.10	✓	10.20	✗	62.10	✓
FGCMA-P	13.28	✓	2.16	✓	3.80	✓	83.90	✓

3.2. Durability test results

3.2.1. Results of the Cantabro test. Plot of the Cantabro loss result is presented in Figure 3. The plot visually signified that POFA addition in CMA improved the durability of the mixtures by 50% for both CQS-1h and RS-1K. This is deduced from the Cantabro loss percentage, which means that lower Cantabro losses suggest better durability. Generally, the result indicates that CQS-1h exhibits lesser losses than RS-1K mixtures; thus, CQS-1h has higher adhesion properties and durability.

The result proves the efficacy of POFA's pozzolanic attribute in enhancing aggregate-binder bond thereby improving cracking/abrasion resistance, and durability of asphalt mixes. Even in concrete mixes, despite the extended duration of pozzolanic reaction and cement hydration of up to a year or more, yet, the significant strength attainment occurs within the first 28 days. Similarly for CMA, full strength is attained within a week or less of casting. The durability of FGCMA-P mixtures was improved for CQS-1h and RS-1K by 55.2% and 47.4%, respectively, compared to FGCMA-C. This result is significantly appreciable considering the fact that the test was specifically designed for HMA mixtures. The result in Figure 3 further explained the desirability of the polymer-modified CQS-1h emulsion over the RS-1K. Furthermore, the durability of dense-graded CMA mixtures in terms of Cantabro loss was reported to be influenced by void content, presence of polymer, and aggregate gradation and type [43]. Thus, the polymer matrix in CQS-1h improved the binder-aggregate adhesion, enhancing the resistance of CMA mixture to impact and abrasive forces better than RS-1K.

Therefore, the addition of POFA in CMA improves abrasive and impact damage of the mixture by roughly 50% based on the result of Cantabro test presented in Figure 3.

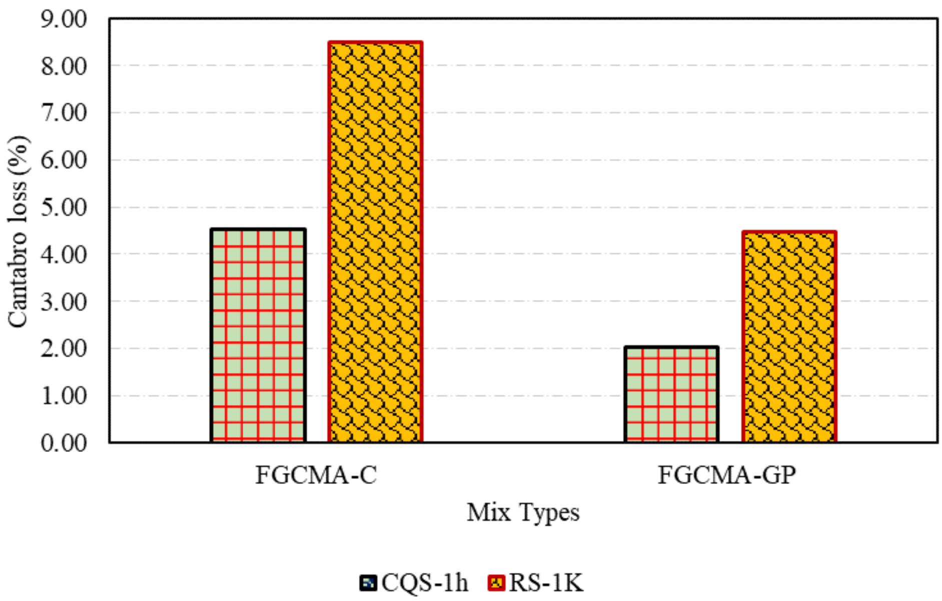

Figure 3. Cantabro loss plot for CQS-1h and RS-1K.

3.2.2. Results of the Modified Lottman test. The result of the modified Lottman's test is presented in Figure 4. From Figure 4 it can be deduced that dry ITS is higher compared to wet ITS for all mix types, reason being that moisture reduces bond strength in asphalt mixtures and in turn impairs mixture durability [54]. ITS values could be used to define an asphalt mixture's cracking resistance – higher ITS values denote enhanced resistance to fatigue cracking. However, this fact is to be treated with caution as specific tests are available for evaluating the cracking resistance of asphalt mixtures.

The addition of POFA in the mix improves both the ITS and TSR of both CQS-1h and RS-1K emulsions. The TSR limit for HMA was plotted as a basis for comparison to that of the FGCMA-4.75 mm mixes. The plot is represented with a straight line at the 80% mark of the TSR axis as in Figure 4. In spite the fact for their lower TSR compared to the standard HMA mix, yet, the FGCMA-P has higher TSR than FGCMA-C for CQS-1h and RS-1K by 7.09% and 11.09% respectively suggesting improved resistance to moisture damage. Hence, the POFA modified mix (FGCMA-P) has improved durability and moisture damage resistance compared to the control mixture (FGCMA-C).

Unlike CQS-1h optimised mix, the margin of improvement in TSR between FGCMA-P and FGCMA-C for RS-1K is relatively small. Furthermore, contrary to expectations that the polymer-modified emulsion mixtures will yield better moisture damage resistance, the FGCMA-GP of RS-1K has higher TSR than that of CQS-1h emulsion.

It is worth mentioning that the aggregate type and gradation affects the moisture damage resistance of CMA more than does emulsion type. It was reported that limestone aggregate in CMA has superior moisture damage resistance than granite aggregate for the same emulsion type [9]. To this end, there is a need to explore the efficacy of POFA in improving CMA durability of mixtures made with varying types of aggregate to arrive at a robust conclusion.

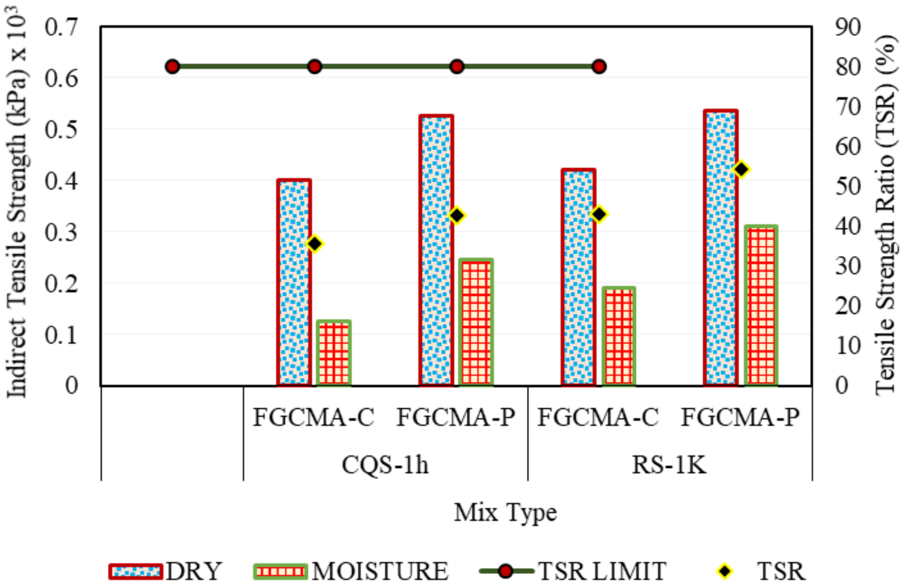

Figure 4. result of the Indirect Tensile Strength and Tensile Strength Ratio.

4. Conclusion

Based on the data analysed and result evaluated, the following conclusions were drawn:

- Despite of CMA's attractive features of being cost-effective and energy efficient mixture, yet, it has a number of setbacks, prominent of which are weak early strength and durability.
- The modified Marshall design for CMA is adequate in designing dense-graded mixes, however, the Marshall verification of result revealed the FGCMA-C to fail in terms of void content as it has higher VTM above the 3-5% stipulated by MoRTH. Thus, the need to devise an encompassing universal design approach for CMA to cater for this concern.
- Fine-graded cold mix asphalts (FGCMA) have better durability compared to other gradation types, and the influence of POFA filler on the durability of FGCMA-4.75 mm was evaluated in terms of Cantabro and moisture damage tests.
- POFA addition has improved the abrasion resistance of FGCMA-4.75 mm by 50% compared to unmodified mixes based on the Cantabro result.
- The modified Lottman test result in addition to revealing the efficacy of POFA in improving the cracking resistance of CMA, also suggest its ability in enhancing CMA's resistance to moisture damage.

5. References

[1] Nur Naqibah Kamarudin S, Rosli Hainin M, Khairul Idham Mohd Satar M and Naqiuddin Bin Mohd Warid M 2018 Comparison of Performance between Hot and Warm Mix Asphalt as Related to Compaction Design *J. Phys. Conf. Ser.* **1049**

[2] Thives L P and Ghisi E 2017 Asphalt mixtures emission and energy consumption: A review *Renew. Sustain. Energy Rev.* **72** 473–84

[3] Rubio M C, Martínez G, Baena L and Moreno F 2012 Warm Mix Asphalt: An overview *J. Clean. Prod.* **24** 76–84

[4] Jain S and Singh B 2021 Cold mix asphalt: An overview *J. Clean. Prod.* **280** 124378

[5] Usman K R, Hainin M R, Satar M K I, Warid M N M and Giwangkara G G 2020 Rheological criteria assessment of a rapid setting emulsion as compared to quick set for emulsified asphalt cold mixes *IOP Conference Series: Earth and Environmental Science* vol 476 p 2

[6] Dulaimi A, Al Nageim H, Ruddock F and Seton L 2017 High performance cold asphalt concrete mixture for binder course using alkali-activated binary blended cementitious filler *Constr. Build. Mater.* **141** 160–70

[7] Usman K R, Hainin M R, Mohd Satar M K I, Mohd Warid M N, Kamarudin S N N and Abdulrahman S 2021 Palm oil fuel ash application in cold mix dense-graded bituminous mixture *Constr. Build. Mater.* **287** 123033

[8] Khalid H A and Monney O K 2009 Moisture damage potential of cold asphalt *Int. J. Pavement Eng.* **10** 311–8

[9] Ling C, Hanz A and Bahia H 2014 Evaluating Moisture Susceptibility of Cold-Mix Asphalt *Transp. Res. Rec. J. Transp. Res. Board* **2446** 60–9

[10] Abdulrahman S, Hainin M R, Satar M K I M, Hassan N A and Usman A 2019 Rutting and Moisture Damage Evaluation of Warm Mix Asphalt Incorporating POFA Modified Bitumen *Int. J. Eng. Adv. Technol.* **9** 90–8

[11] Kumar P and Anand P 2012 Laboratory Study on Moisture Susceptibility of Dense Graded Mixes *J. Transp. Eng.* **138** 105–13

[12] Al-Merzah S, Al-Busaltan S and Nageim H Al 2019 Characterizing Cold Bituminous Emulsion Mixtures Comprised of Palm Leaf Ash *J. Mater. Civ. Eng.* **31** 04019069

[13] Usman K R, Hainin M R, Satar M K I, M Warid M N and Abdulrahman S 2020 Modified Marshall Test assessment for emulsified asphalt cold mixes *IOP Conf. Ser. Earth Environ. Sci.* **498** 012023

[14] Ronald M and Luis F P 2016 Asphalt emulsions formulation: State-of-the-art and dependency of formulation on emulsions properties *Constr. Build. Mater.* **123** 162–73

[15] Thanaya I N A 2003 *Improving the performance of cold bituminous emulsion mixtures (CBEMs) : incorporating waste*

[16] Huang C W, Yang T H and Lin G B 2020 The Evaluation of Short- And Long-Term Performance of Cold-Mix Asphalt Patching Materials *Adv. Mater. Sci. Eng.*

[17] Oluwasola E A, Hainin M R and Aziz M M A 2016 Comparative evaluation of dense-graded and gap-graded asphalt mix incorporating electric arc furnace steel slag and copper mine tailings *J. Clean. Prod.* **122** 315–25

[18] Usman K R, Hainin M R, Idham M K, Warid M N M, Yaacob H, Hassan N A, Azman M and Puan O C 2019 Performance evaluation of asphalt micro surfacing – a review *IOP Conf. Ser. Mater. Sci. Eng.* **527** 012052

[19] Yaacob H, Chang F L, Rosli Hainin M and Jaya R P 2015 Curing of asphalt emulsified tack coat subjected to malaysian weather conditions *J. Mater. Civ. Eng.* **27** 1–10

[20] JKR 2008 JKR/SPJ/2008-S4 Standard Specification for Road Works Part4 Flexible Pavement *JKR Specification for Road Works Part4 Flexible Pavement* pp 1–187

[21] American Society for Testing and Materials 2016 ASTM C150/C151 - 11 Standard Specification for Portland Cement (ASTM International, West Conshohocken, PA.) pp 1–14

[22] Du Y, Kong L and Wei T 2019 Laboratory investigation into early-age strength improvement of cold recycled asphalt mixture containing asphalt emulsion and cement *Adv. Civ. Eng.* 1–10

[23] Jiang J, Ni F, Zheng J, Han Y and Zhao X 2020 Improving the high-temperature performance of cold recycled mixtures by polymer-modified asphalt emulsion *Int. J. Pavement Eng.* **21** 41–8

[24] Bueno E T, Paris J M, Clavier K A, Spreadbury C, Ferraro C C and Townsend T G 2020 A review of ground waste glass as a supplementary cementitious material: A focus on alkali-silica reaction *J. Clean. Prod.* **257** 120180

[25] Hafizah N, Khalid A, Hussin M W, Mirza J, Farhayu N, Ismail M A, Lee H, Mohamed A and Putra R 2016 Palm oil fuel ash as potential green micro-filler in polymer concrete *Constr. Build. Mater.* **102** 950–60
[26] Salam M, Safiuddin M and Jumaat M 2018 Durability Indicators for Sustainable Self-Consolidating High-Strength Concrete Incorporating Palm Oil Fuel Ash *Sustainability* **10** 2345
[27] Aldahdooh M A A, Bunnori N M and Johari M A M 2013 Development of green ultra-high performance fiber reinforced concrete containing ultrafine palm oil fuel ash *Constr. Build. Mater.* **48** 379–89
[28] Megat Johari M A, Zeyad A M, Muhamad Bunnori N and Ariffin K S 2012 Engineering and transport properties of high-strength green concrete containing high volume of ultrafine palm oil fuel ash *Constr. Build. Mater.* **30** 281–8
[29] Awal A S M A and Hussin M W 1997 The effectiveness of palm oil fuel ash in preventing expansion due to alkali-silica reaction *Cem. Concr. Compos.* **19** 367–72
[30] Tangchirapat W, Jaturapitakkul C and Chindaprasirt P 2009 Use of palm oil fuel ash as a supplementary cementitious material for producing high-strength concrete *Constr. Build. Mater.* **23** 2641–6
[31] Ranjbar N, Mehrali M, Alengaram U J, Simon H and Metselaar C 2014 Compressive strength and microstructural analysis of fly ash / palm oil fuel ash based geopolymer mortar under elevated temperatures *Constr. Build. Mater.* **65** 114–21
[32] Abdullah K and Hussin M 2010 Fire Resistance Properties of Palm Oil Fuel Ash Cement Based Aerated Concrete *Concr. Res. Lett.* **1** 1–5
[33] Momeen M, Islam U, Mo K H and Alengaram U J 2016 Durability properties of sustainable concrete containing high volume palm oil waste materials *J. Clean. Prod.* **137** 167–77
[34] Awal A S M A and Shehu I A 2013 Evaluation of heat of hydration of concrete containing high volume palm oil fuel ash *Fuel*
[35] Adebayo Mujedu K, Ab-Kadir M A and Ismail M 2020 A review on self-compacting concrete incorporating palm oil fuel ash as a cement replacement *Constr. Build. Mater.* **258** 119541
[36] Islam A, Alengaram U J, Jumaat M Z, Bashar I I and Kabir S M A 2015 Engineering properties and carbon footprint of ground granulated blast- furnace slag-palm oil fuel ash-based structural geopolymer concrete *Constr. Build. Mater.* **101** 503–21
[37] Tangchirapat W, Khamklai S and Jaturapitakkul C 2012 Use of ground palm oil fuel ash to improve strength , sulfate resistance , and water permeability of concrete containing high amount of recycled concrete aggregates *Mater. Des.* **41** 150–7
[38] Hamada H M, Jokhio G A, Yahaya F M, Humada A M and Gul Y 2018 The present state of the use of palm oil fuel ash (POFA) in concrete *Constr. Build. Mater.* **175** 26–40
[39] Nassar A I, Mohammed M K, Thom N and Parry T 2016 Mechanical, durability and microstructure properties of Cold Asphalt Emulsion Mixtures with different types of filler *Constr. Build. Mater.* **114** 352–63
[40] Nassar A I, Mohammed M K, Thom N and Parry T 2018 Characterisation of high-performance cold bitumen emulsion mixtures for surface courses *Int. J. Pavement Eng.* **19** 509–18
[41] Abdullah N and Sulaim F 2013 The Oil Palm Wastes in Malaysia *Biomass Now - Sustainable Growth and Use* (InTech)
[42] Joni H H 2018 Studying the effect of emulsified asphalt type on cold emulsified asphalt mixtures properties *IOP Conf. Ser. Mater. Sci. Eng.* **433**
[43] MoRTH 2013 Specifications for Road and Bridges Works *Indian Roads Congress on behalf of the Govet. of India, Ministry of Road Transport & Highway* vol 1 pp 234–683
[44] American Society for Testing Materials 2015 ASTM D6926. Standard Practice for Preparation of Bituminous Specimens Using Marshall (ASTM International, West Conshohocken, PA.)
[45] Dash S S and Panda M 2018 Influence of mix parameters on design of cold bituminous mix *Constr. Build. Mater.* **191** 376–85
[46] Ling C and Bahia H U 2018 Development of a volumetric Mix Design Protocol for Dense-Graded Cold Mix Asphalt *J. Transp. Eng. Part B Pavements* **144** 04018039

[47] Thanaya I N A, Zoorob S E and Forth J P 2009 A laboratory study on cold-mix, cold-lay emulsion mixtures *Proc. Inst. Civ. Eng. - Transp.* **162** 47–55
[48] Du S 2015 Performance Characteristic of Cold Recycled Mixture with Asphalt Emulsion and Chemical Additives *Adv. Mater. Sci. Eng.* **2015** 2–8
[49] American Society for Testing Materials 2015 ASTM D6927. Standard Test Method for Marshall Stability and Flow of Asphalt Mixtures (ASTM International, West Conshohocken, PA.)
[50] American Society for Testing and Materials 2015 StandardTheoretical Maximum Specific Gravity and Density of Bituminous Paving Mixtures *D2041/D2041M − 11.* (ASTM International, West Conshohocken, PA.)
[51] Maleka A M, Hamad A W and Jaya R P 2015 Effect of Palm Oil Fuel Ash (POFA) on the Durability of Asphaltic Concrete *Appl. Mech. Mater.* **744–746** 1560–5
[52] Cox B C, Smith B T, Howard I L and James R S 2017 State of Knowledge for Cantabro Testing of Dense Graded Asphalt *J. Mater. Civ. Eng.* **29** 04017174
[53] Texas DoT M and T D 2014 Cantabro loss *TxDoT* pp 3–5

Acknowledgments
The authors would like to thank Universiti Teknologi Malaysia (UTM) and Ministry of Higher Education (MoHE) for providing financial support under the Research grant No. FRGS/1/2019/TK06/UTM/02/1. In addition, the main Author wish to appreciate the support from the Federal Government of Nigeria’s Tertiary Education Trust (TETFund) intervention/sponsorship through Nuhu Bamalli Polytechnic.