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#### Article

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## Article

# The Impact of Cement Kiln Dust and Cement on Cold Mix Asphalt Characteristics at Different Climate

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**Abstract:** Cold bitumen emulsion mixtures (CBEMs) are made up of the same materials that are used in hot mixes. However, asphalt emulsion and water are used in such mixes. To date, many countries are still not using these mixes as a structure layer. This can be attributed mainly to their low resistance to rainfall, long curing time and low early strength. The addition of cementitious filler to CBEMs as a clean paving material is a potential technique to achieve superior mechanical qualities. The aim of this research is to compare improved CBEMs that might be used as a wearing surface to hot mix asphalt (HMA). These improvements were carried out through the use of a combination of cement and limestone, or a combination of ordinary Portland cement (OPC) and cement kiln dust (CKD). CBEMs were prepared according to Egyptian and British gradations using different percentages of ordinary Portland cement (OPC), CKD, and limestone. This may offer a new cold bitumen emulsion mixture to be used as a structural pavement layer in such countries. The main tests performed for the assessment of the mixes in this research are indirect tensile stiffness modulus, fatigue resistance, and resistance to rutting at different temperatures (20°C, 45°C, and 60 °C). The results show that adding OPC to CBEMs enhanced the results in terms of ITSM, rutting and fatigue resistance. However, significant improvements were made by binary filler made of CKD and OPC to the said mechanical properties in terms of both UK and Egyptian gradations. The ITSM values for both CBEM<sub>UK6</sub> and CBEM<sub>Eg6</sub>, which contain 80% OPC + 20% CKD, improved by around 8 and 9 times in comparison to CBEM<sub>UK1</sub> and CBEM<sub>Eg1</sub>, which contain 20% OPC + 80% L.S, respectively.

**Keywords:** cold mix asphalt; rutting; fatigue life; hot and cold climates

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## 1. Introduction

Highway engineers and researchers are looking for innovative pavements to address growing environmental and economic challenges, and investigate new methods of pavement maintenance strategies [1–3]. The cold bitumen emulsion mixture (CBEM) is classified as cold mix asphalt. It is the most well-known type of cold mix asphalt. It is a bituminous material that is made at room temperature. When cold mix asphalt is utilised instead of standard hot mix asphalt, there are several environmental and economic benefits. CBEMs are easy to make in general, and are ideal for low- to medium-traffic circumstances, rural places, and small-scale projects such as reinstatement. Furthermore, CBEMs emit negligible CO<sub>2</sub> and other fume emissions, require little energy to manufacture, and are extremely safe to use [4,5]. Nevertheless, to date, there is no universally accepted mix design method for CBEMs.

There have been more than a few trials attempting to upgrade the mechanical properties of CBEMs. These have replaced conventional filler with different additives to solve the main disadvantage of cold mix asphalt, which is its weak strength in early life. This is the main reason for not using cold mix asphalt as a structure layer in road pavements (wearing surface, binder course, or bituminous base course), in comparison to HMA. The other disadvantages are the long curing time, and its inability to resist rainfall [6]. Several additives have been used to solve these shortcomings; the major ones are cement, fly ash, fibre, and chemical products.

Schmidt et al. [7] tried to develop the curing time by adding cement to the cold mix asphalt. The findings revealed that the mix cured faster, and the modulus of resilience of the treated mix was also rapidly improved. Li et al. [8] added cement to improve the fatigue life and increase the flexibility of asphalt concrete. Brown and Needham [9] reported that adding cement made emulsion charges more positive. Pouliot et al. [10] highlighted the hydration process between cement and the added emulsion. Song et al. [11] suggested using asphalt emulsion as a polymeric admixture. The experimental results show that increasing the polymer–cement ratio caused a reduction in the adhesiveness and compressive strength of the mortar, as well as improvements in water resistance and carbonation resistance. Thanaya et al. [12] used rapid-setting cement to accelerate the early strength and minimise the curing time. However, using cement only has a considerable CO<sub>2</sub> impact, and cement is also considered a costly material. Thus, other trials have used cement with by-products or waste materials as supplementary materials [13–15].

Thanaya et al. [16] incorporated fly ash into cold bituminous emulsion mixtures. The experimental results show improvements in volumetric properties, creep under repeated load, and stiffness modulus compared to conventional CBEMs. Other trials have studied the effect of fly ash on cold mixes [17–19]. All of these researchers reported the effect of fly ash's mechanical properties, such as stiffness modulus, creep stiffness, resilient modulus and resistance to water sensitivity.

Bueno et al. [20] examined the influence of polypropylene fibre on the mechanical properties of cold mix asphalt. The results indicate that, by adding fibre to CBEMs, a small variation in mixture strength was caused, in addition to a reduction in the resilient modulus of mixtures, the Marshall Stability, and the dry density of the cold mix.

Portland cement has been broadly employed to substitute traditional limestone filler in CBEMs manufacturing to offer adequate early-age strength [21], overcome concerns about excessive air voids [22], high water sensitivity [23] and low early-age strength [21], and encourage the usage of such mixes. Filler, as one of the raw materials in the asphalt mixture, mainly fills the air voids and reduces the gap between aggregates [24]. It is useful for managing the mixture's performance [25,26]. As a result, proper filler selection and combination has been deemed a useful method for improving CBEMs' performance.

The use of CKD as a partial OPC replacement material in the preparation of binary blended cement has not been fully established in the current body of literature, despite the existence of some studies on CBEMs' production with OPC. In addition, the comparison of two different aggregate gradations from different climates has not been fully addressed in the previous studies. To date, the performance of the CBEMs is still inferior to conventional hot mix asphalt. So, researchers are working to develop CBEMs that have mechanical performances equal to or even better than the HMA. The aim of this study is to investigate whether OPC and CKD can be used to produce a novel CAEM that can be used as a sustainable pavement material. To explore the strength development of CAEM, a comprehensive set of laboratory experiments was conducted. In this research, six mixes of CBEMs with OPC and CKD, and CBEMs with OPC and limestone, are tested against Egyptian and British gradations. Firstly, an ITSM will be performed to determine the highest stiffness modulus of the different mixes. Then, the selected mixes for Egypt and Britain will be used to complete the wheel-track test at different temperatures, as well as a fatigue test. A comparison between the two types of hot mix asphalt (soft and hard) and the improved CBEMs was also performed. Moreover, the same aggregate type and gradation

are used to prepare traditional hot mixture samples with 5% and 5.3% binder content, in order to match the requirements of AASHTO R12-85 2002 and BS EN 4987 2005 in Egypt and Britain, respectively.

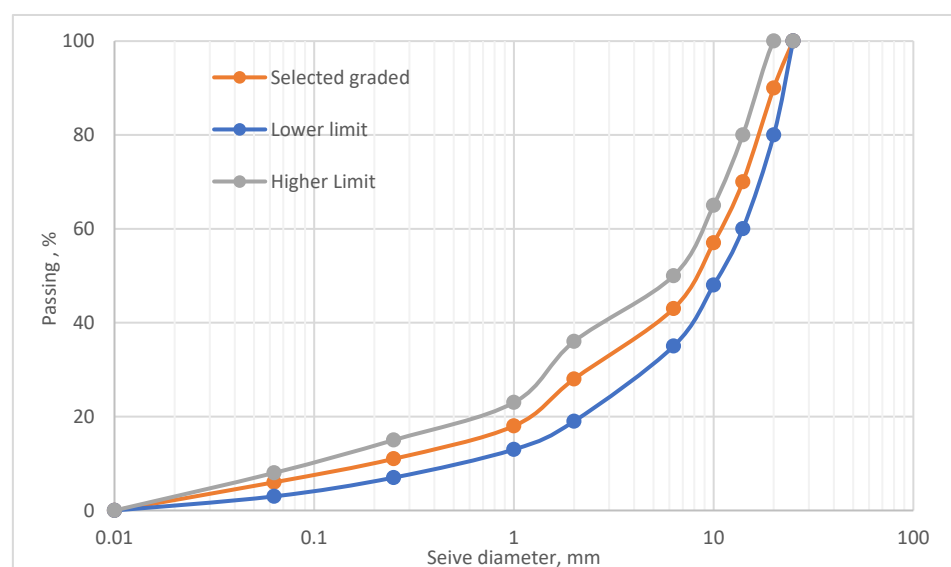
## 2. Material and Testing

### 2.1. Materials

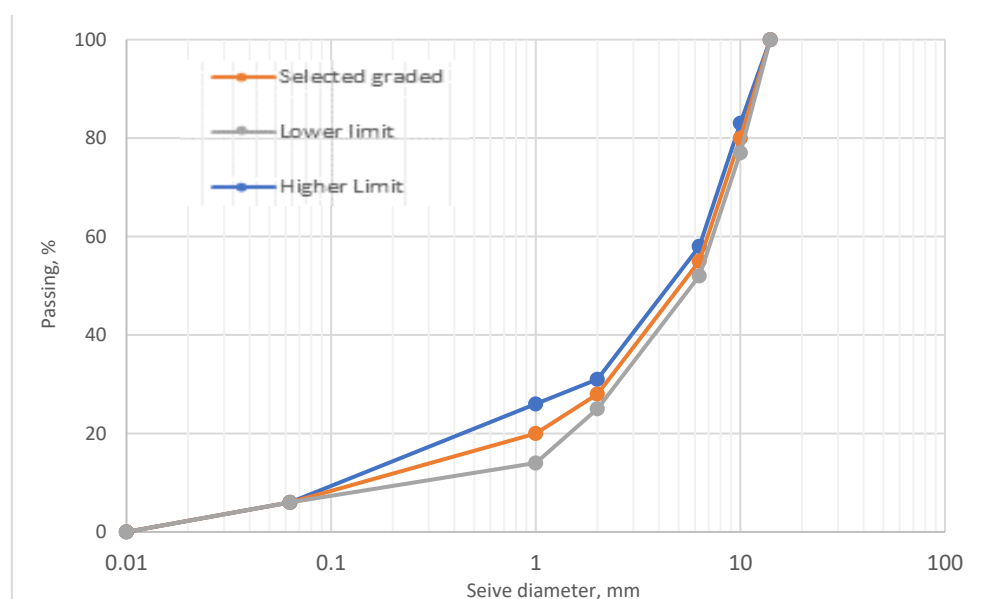
In this research, crushed granite aggregates were used. 4C and 14C dense- and close-graded surface course mixtures were selected because they are widely used in designing surface asphalt concrete mixtures in both countries. The difference between two gradations is shown in the design of the asphalt mixtures in both countries; the maximum nominal size in the British specifications (14 mm) is less than that in the Egyptian specifications (20 mm), which permits a larger surface area and fewer interstitial voids, and thus improves the compaction process.

The opposing charge on the granite aggregate surface attracts the positively charged cationic emulsifier. This achieves the best adherence between the aggregate and the emulsion.

Figures 1 and 2 show the particle size distributions of these gradations. The physical properties are given in Table 1. The different mixes of CBEMs with two types of filler (OPC with limestone or OPC with CKD) are illustrated in Table 2. The total percentage of filler used was 6% of the total aggregate weight. The bitumen binder 50–70 (CB3-50) was used to prepare the cold mix asphalt. The comparison between the cold mix asphalt and the hard hot mix asphalt, as well as the soft hot mix asphalt, was conducted using bituminous binder 61 and 143 pen grades. The properties of both the bituminous emulsion and the bitumen binder used in this study are shown in Table 3. The cold mix asphalt and hot mix asphalt specimens were mixed and compacted at laboratory temperatures of 20–25 °C and 160–170 °C, respectively.



**Figure 1.** 4C dense-graded surface course Egyptian gradation. Reprinted with permission from Ref. [27]. Copyright 2020 National Center for Housing and Building Research.



**Figure 2.** 14C close-graded surface course British gradation. Reprinted with permission from Ref. [28]. Copyright 2013 The British Standards Institution.

**Table 1.** The physical properties of the aggregates used.

Properties	Value
Fine aggregate	
Absorption of Water	1.55%
Bulk Density	2.66 gm/cm <sup>3</sup>
Apparent Density	2.71 gm/cm <sup>3</sup>
Coarse aggregate	
Absorption of Water	0.61%
Bulk Density	2.77 gm/cm <sup>3</sup>
Apparent Density	2.80 gm/cm <sup>3</sup>

**Table 2.** Mix types and percentages.

Mix Type	Filler	Mix Type	Filler
CBEM <sub>Eg1</sub>	20% OPC + 80% L.S	CBEM <sub>UK1</sub>	20% OPC + 80% L.S
CBEM <sub>Eg2</sub>	50% OPC + 50% L.S	CBEM <sub>UK2</sub>	50% OPC + 50% L.S
CBEM <sub>Eg3</sub>	80% OPC + 20% L.S	CBEM <sub>UK3</sub>	80% OPC + 20% L.S
CBEM <sub>Eg4</sub>	20% OPC + 80% CKD	CBEM <sub>UK4</sub>	20% OPC + 80% CKD
CBEM <sub>Eg5</sub>	50% OPC + 50% CKD	CBEM <sub>UK5</sub>	50% OPC + 50% CKD
CBEM <sub>Eg6</sub>	80% OPC + 20% CKD	CBEM <sub>UK6</sub>	80% OPC + 20% CKD

**Table 3.** Bituminous emulsion and bitumen binder properties.

Bitumen Emulsion		Bituminous Binder		100–150	50–70
Properties	Value	Properties		Value	Value
Appearance	Black to dark brown liquid	Appearance		Black	Black
Relative density at 15 °C, g/mL	1.06	Softening point, °C		43	48.5
Boiling point, °C	101	Penetration, 25 °C		143	61
Residue by distillation, %	50	Kinematic viscosity at 135 °C		169	321
		Density at 25 °C		1.00	1.01

## 2.2. Sample Preparation

The Asphalt Institute Method (MS-14) was adopted by the Asphalt Institute [29] to prepare cold mix asphalt specimens. Only one change was made to this method—instead of the Marshall Test, an indirect tensile strength test was used. The procedural steps are summarised in Table 4.

**Table 4.** Design mix procedures according to the Asphalt Institute. Reprinted with permission from Ref. [29]. Copyright 1997 Asphalt Institute.

According to the Asphalt Institute (1989)	Egyptian Samples	British Samples
The initial residual bitumen content (P) (%)	6.16	6.16
The initial emulsion content (IEC) = (P/0.5) (%)	12.32	12.32
Pre-wetting water content (%)	3.00	3.0
The optimum total liquid content at compaction (%)	13.5	14.0
The optimum residual bitumen content (%)	6.3	6.5

## 2.3. Testing

To analyze the mechanical properties of the developed CBEMs, three types of fundamental tests were conducted (ITSM test, fatigue test, and wheel-tracking test) to explore the influences of both CKD and OPC, according to Egyptian and British gradations.

### 2.3.1. Indirect Tensile Stiffness Modulus (ITSM)

ITSM is a non-destructive test that determines the stiffness modulus of bituminous mixes, both hot and cold. The test was conducted following BS EN 12697-26 [30]. A steel load frame, a load cell with a pneumatic load actuator, a deformation measurement system, and a personal computer that records the electrical signals from the load actuator on five monitors make up the majority of the test equipment. Figure 3 depicts the test equipment within the refrigerated incubator, as well as the test specimen mounted on the loading platens and connected to the computer that measures deformation. The experiments were carried out at a constant temperature of 20 degrees Celsius. Table 5 depicts the test circumstances. The HYD 25 device from Cooper Research Technology was used to test ITSM for various specimens.



**Figure 3.** Cooper Research Technology HYD 25 testing apparatus.

**Table 5.** ITSM test conditions.

Item	Range
Test temperature (°C)	20 ± 0
Specimen diameter (mm)	100 ± 3
Compaction Marshall	50 for each face
Rise time	124 ± 4 ms
Transient peak horizontal deformation	5 µm
Poisson's ratio	0.35
Specimen thickness (mm)	63 ± 3
Loading time	3–300 s
Specimen temp. conditioning	4 h before testing
No. of conditioning plus	10
No. of test plus	5

### 2.3.2. Fatigue Resistance

Fatigue damage occurs when an asphalt layer is subjected to a large number of bending force cycles [31]. The Cooper four-point bending test is used to measure the fatigue life of materials subjected to bending forces. The fatigue life is the number of cycles after which the stiffness is half of what it was at the start [32]. After the first 100 cycles of repeated loading, the specimen's initial stiffness will be determined automatically. The specimen is a prismatic beam that is loaded sinusoidally in either the controlled strain or the stress mode. The tests were carried out at a displacement-controlled temperature of 20 °C, with a strain level of 105 to 106 load repetitions (at 10 Hz), until the force required for the prescribed displacement was reduced to half its starting value. As illustrated in Figure 4, both graphical and tabular data were displayed on screen during testing, and the test data were saved to a disc in a Microsoft Excel TM-compatible format. Table 6 depicts the test circumstances. Fatigue resistance according to BS EN 12697-24 [33].



**Figure 4.** Cooper four-point apparatus.

In the fatigue test, prismatic specimens were employed, and their total length, width, and height were 400 mm, 50 mm, and 50 mm, respectively. For each mixture, three duplicated beam specimens were tested, and the average value was calculated.

**Table 6.** Four-point test conditions.

Item	Range
Force transducer	$\pm 5\text{Kn}$
Specimen dimensions (mm)	$400 \times 50 \times 50$
Frequency	10 Hz
Specimen transducer range	$\pm 1\text{ mm}$
Test temperature ( $^{\circ}\text{C}$ )	$20 \pm 0.5$
Strain	$150, 200 \times 10^{-6}\text{ m/m}$
Test frame dimensions (mm)	$440 \times 190 \times 570$
Test end value	50%
Specimen temp. conditioning	14 days before testing

### 2.3.3. Resistance to Rutting

Permanent deformation, mainly referring to rutting, is one of the main distress modes of asphalt pavement [34,35]. The deformation expected to occur in asphaltic materials under wheel loading is predicted using an autonomous wheel-tracking tester (HYCZ-5). The wheel-tracking equipment is shown in Figure 5. A Cooper roller compactor was used to make the slabs. The slab was  $400 \times 305 \times 50\text{ mm}$  in size. Table 7 depicts the test circumstances. The test was carried out at various temperatures, including 20, 45, and 60 degrees Celsius, to evaluate the materials under various weather situations. The rut depth under load was measured in relation to the wheel load. Resistance to rutting at different temperatures was determined in accordance with BS EN 12697-22 [36].





**Figure 5.** Wheel-tracking machine.

**Table 7.** Wheel-track test conditions.

Item	Range
Slab dimension (mm)	400 x 305 x 50
Trolley travel speed	42s/min $\pm$ 1s/min
Trolley travel distance	230 $\pm$ 10 mm
Ground pressure test round	0.7MPa $\pm$ 0.05 MPa
Rutting experimental time	20–300min
Test temperature (°C)	20, 45, and 60°C $\pm$ 0.1
Specimen temp. conditioning:	
At oven (40 °C)	14 day
At test temperature	4 hours before test beginning

### 3. Results and Discussion

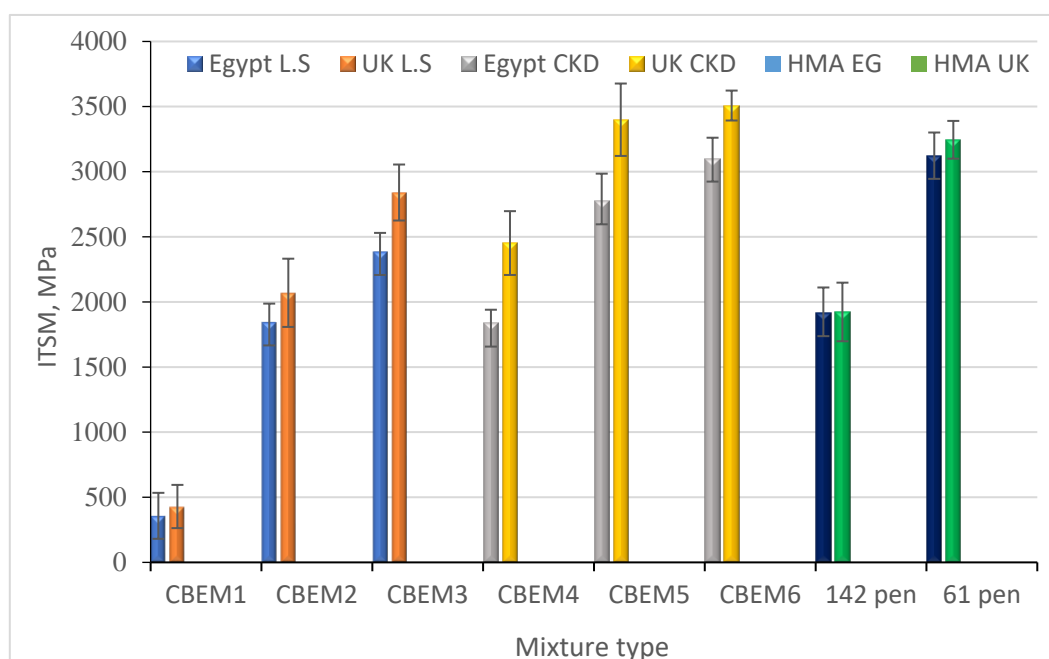
#### 3.1. Indirect Tensile Stiffness Modulus

Following the BS EN 12697-26 specification [30], all specimens were tested firstly at an age of 2 days to assess the use of OPC with limestone and OPC with CKD as a filler at different percentages in CBEMs, according to Egyptian and British gradations. Accordingly, the best one—the one that gave highest ITSM for the different mixes—was chosen to complete the ITSM test at ages of 7, 14 and 28 days, and this ratio was used on the following tests, i.e., fatigue resistance and resistance to rutting.

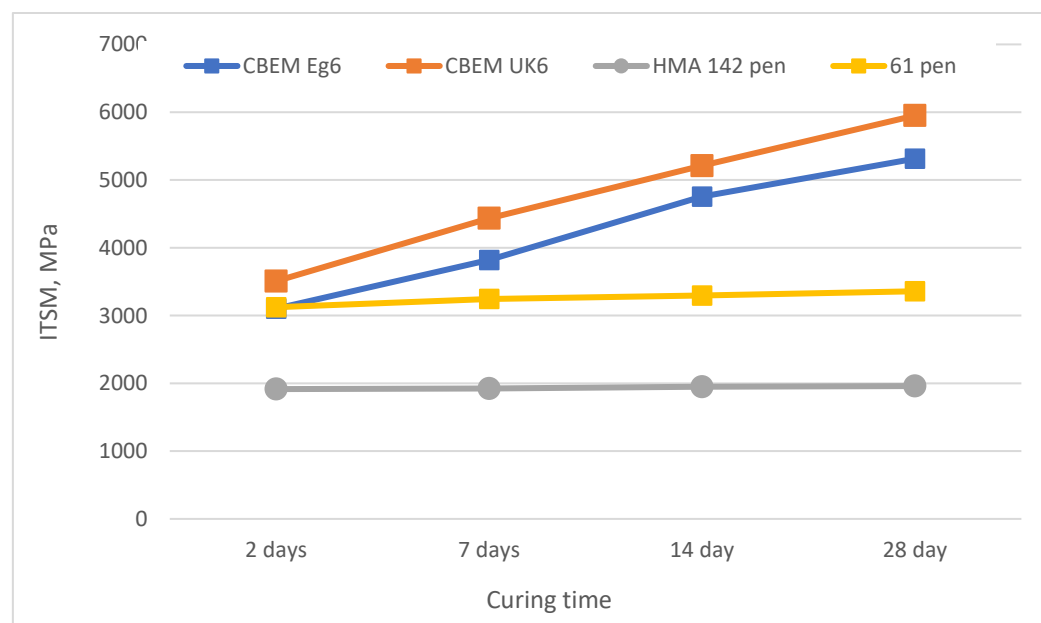
For the mix of OPC with conventional limestone (LS), as shown in Figures 6 and 7, it is obvious that the stiffness modulus for the British gradation is improved in comparison to that for the Egyptian gradation at different ages and mixes. This may be attributed to the difference in gradation, which may allow higher compaction in the British samples than in the Egyptian samples. A gradual increment is seen in ITSM, with the increased percentage of OPC in the mix at age 2 days under both Egyptian and British gradations. For the Egyptian gradation at 2 days, the ITSM for CBEM3 (80% OPC with 20% limestone) compares reasonably with soft HMA. However, under the British gradation, CBEM3 gives a higher value than soft HMA.

For the mix of OPC with CKD at different ages, mixes and gradations, the stiffness modulus of the cold mix with CKD is higher than the stiffness modulus of the cold mix with limestone under both Egypt and British gradations. This indicates a significant improvement in the stiffness modulus resulting from the addition of CKD to the CBEMs. For both the British gradation and the Egyptian gradation, the ITSM values of CBEM at 2 and 7 days are higher than the ITSM values for soft and hard HMA. At different ages, the ITSM

for CBEM6 under Egyptian and British gradations gave higher values than soft or hard HMA, with very little increment in stiffness modulus for the two types of HMA.



**Figure 6.** ITSM of HMA and CBEMs for different mix types at 2 days.



**Figure 7.** CBEM6 ITSM for the Egyptian and the British CBEMs at different ages.

### 3.2. Fatigue Resistance

Fatigue tests were carried out in accordance with BS EN 12697-24 [33] at a frequency of 10 Hz and a temperature of 20 °C. Figure 8 depicts the results. Table 8 displays the fatigue connections determined for the two countries with different strains (150–200 m/m). The following is a definition of the fatigue–life relationship:

$$\log N_f = f_1 + \log \varepsilon - E_1 f_2 \quad (1)$$

where  $N_f$  is the number of continuous strain applications until the specimen achieves half of its original stiffness,  $\varepsilon$  is the applied strain ( $\mu\text{m/m}$ ),  $f_1$  and  $f_2$  are the regression constants, and  $E_1$  is the elastic modulus of the asphalt layers.

**Table 8.** Fatigue relationship for Egyptian and British standards at 150 and 200 microstrain.

Country	Microstrain	Formula	R <sup>2</sup>	F	Sig.
Egypt	150–200	$Y = 0.256 + 1.998 x$	0.782	9920	0.000
British	150–200	$Y = -0.702 + 4.665 x$	0.854	13,350	0.000

In the formula,  $y$  stands for log cycle, and  $x$  stands for log micro strain multiplied by the inverse of the modulus of elasticity ( $\log \text{microstrain} \times E_1^{-1}$ ). The resulting coefficients of determination ( $R^2$ ) and significance of the F statistics demonstrate the model's reasonably high goodness-of-fit and relevance for prediction. This formula is compatible with most fatigue failure models that look like this (according to Mathew et al.) [37]:

$$N_f = f_1 \varepsilon^{-f_2} E_1^{-f_3} \quad (2)$$

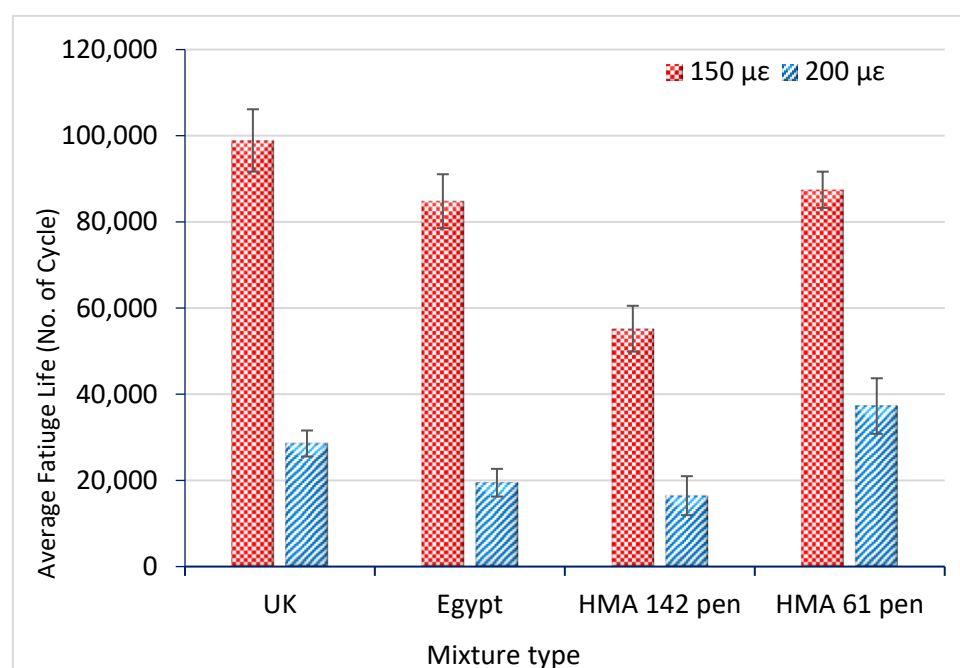
Figure 8 compares the average fatigue lives of the two countries, which correspond to 150 and 200 microstrains, respectively. The stiffness results were well-matched, indicating that the British gradation performed better than the Egyptian gradation.

It can be seen that both the CBEM<sub>UK6</sub> and CBEM<sub>Eg6</sub> had the highest fatigue lives, which are comparable to HMA 61 pen, with an improved performance for the CBEM<sub>UK6</sub>. The modified CBEM<sub>UK6</sub> tolerated the highest number of cycles, and was ranked as the best mix with the longest fatigue life at the 150 strain level.

On the other hand, both the CBEM<sub>UK6</sub> and CBEM<sub>Eg6</sub> achieved better performances in comparison to HMA 141 pen at the 200 strain level.

These results illustrate the significant impact of OPC and CKD on the fatigue life behaviour of both CBEM<sub>UK6</sub> and CBEM<sub>Eg6</sub>, compared to the HMA mixes.

This difference might be due to the stiffness of the said mixes, which depends on the strength of the secondary binder, so these results agree with the results presented in Figure 7. Both the CBEM<sub>UK6</sub> and CBEM<sub>Eg6</sub> mixes (80% OPC with 20% CKD) had a higher ITSM in comparison to both HMAs.



**Figure 8.** Fatigue life for Egyptian and British CBEMs at 150 and 200 microstrain.

### 3.3. Resistance to Rutting

The rut evolutions of six slabs of CBEM6 mix (80% OPC with 20% CKD), as a function of the number of cycles, for both Egyptian and British gradations at the central position are displayed in Figure 9. The rutting resistance test was performed at several temperatures (20, 45, 60 °C) to assess the effect of temperature on the CBEMs in the two countries. This figure shows that, at different temperatures, for CBEMs, the rut depth under the wheel path changes slightly over time, in both the Egyptian gradation and the British gradation. So, replacing LS with both OPC and CKD enhanced the resistance to rutting of different CBEMs at different temperatures. As expected, the rut depth will increase when the temperature is increased. The rut depths at the end of the test for the Egyptian gradation were 0.2985, 0.349, and 0.595 mm, while those for the British gradations were 0.2555, 0.349, and 0.514 mm, at temperatures of 20, 45 and 60 °C, respectively. These values indicate that this mix can be used as a surface course for heavy loads in any weather (cold or hot).

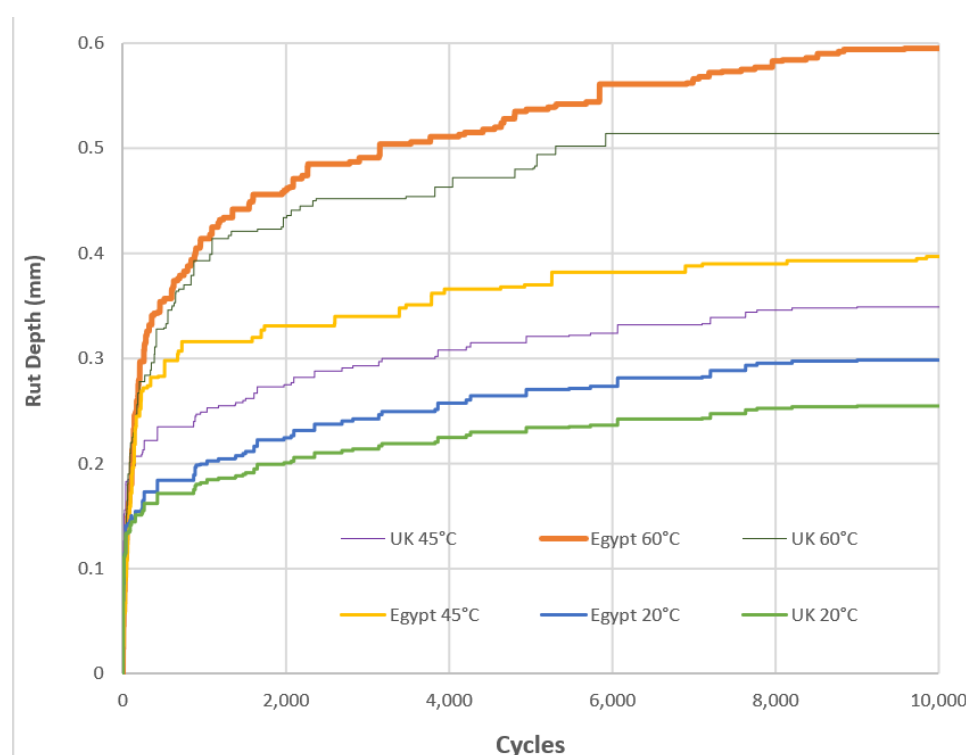


Figure 9. Slab rut depth evolution for CBEM 6 at different temperatures.

## 4. Conclusions

In this research, we conducted an experimental comparison of cold mix surface asphalt gradations in Egypt and Britain. OPC was mixed with either limestone or CKD at different percentages to be used as a filler in new CBEMs. Six cold mixes for each gradation were prepared during the test. ITSM, resistance to rutting at different temperatures (20, 45, and 60 °C) and fatigue resistance were the fundamental tests used in the comparison. The major conclusions of this research are as follows:

- 1) Ordinary Portland cement plays a significant role in improving the stiffness modulus of CBEMs, especially at high percentages (50% and 80% of total filler). This may be attributed to its providing a secondary cementitious binder, and the main role of cement in the hydration process. Increasing OPC from 20% to 80% improved the ITSM for both UK and Egypt gradations by around 8 and 9 times, respectively;
- 2) The best CKD percentage is 20%, which provides the highest ITSM when blended with 80% OPC. Reducing CKD from 80% to 20% improved the ITSM for both UK and Egypt gradations by 140% and 170%, respectively;

- 3) The results of rutting resistance also indicate that replacing LS with both OPC and CKD improved the performance at 20, 45 and 60 °C. It is noted that CBEM6 that have 80% OPC with 20% CKD achieved the highest rut resistance at 20 °C. Thus, the improved CBEM6 mix can be used as a structural layer in different climates, either in Egypt or in Britain;
- 4) The addition of OPC and CKD to CBEMs resulted in a substantial improvement in fatigue life for both British and Egyptian gradations at 150 and 200 microstrains;
- 5) This study showed that the British gradation (14C) gave improved results in all experimental tests compared to the Egyptian gradation (4C) commonly used in Egypt as a surface course. Accordingly, the British one may be a better gradation for Egyptian roads;
- 6) CBEMs with OPC and CKD as filler showed clearly improved mechanical properties, compared to CBEMs with OPC and limestone. Thus, this lab-scale trial should be expanded into the field.

**Author Contributions:** Conceptualization, T.A.-W. and A.D.; methodology, T.A.-W., A.D., H.A.N.; software, T.A.-W. and A.D.; validation, T.A.-W., A.D., H.K.S.; formal analysis, T.A.-W. and A.D.; investigation, T.A.-W., A.D., H.K.S.; resources, T.A.-W. and A.D.; data curation, T.A.-W., A.D., H.K.S.; writing—original draft preparation, T.A.-W. and A.D.; writing—review and editing, T.A.-W. and A.D.; visualization, T.A.-W. and A.D.; supervision, H.A.N. and A.D.; project administration, T.A.-W. and A.D. All authors have read and agreed to the published version of the manuscript.

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