

# EVALUATING AND IMPROVING THE PERFORMANCE OF COLD ASPHALT EMULSION MIXES

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## ABSTRACT

*This paper describes investigation on the performances of cold asphalt emulsion mixes (CAEMs). The type of emulsion used was a cationic asphalt emulsion. The investigation was carried out at Leeds University, United Kingdom (UK). The objective of the experiments was to evaluate and to improve the performances of cold mixes and compared with hot mixes. For optimising the performances of the cold mixes, a target porosity of five to ten percent and indirect tensile stiffness modulus (ITSM) value of 2000 MPa was selected, suitable for low to medium trafficked roads. A simplified mix design procedure was used for producing the cold mixes. It was found that when properly designed, at full curing conditions, the stiffness (ITSM) of CAEMs were found to be very comparable to those of hot mixes. Test results also show that the addition of cement in the amount of one to two percent by mass of aggregates significantly improved the mechanical performance of cold asphalt mixes.*

**Keywords:** cold mix, asphalt emulsion.

## INTRODUCTION

CAEMs principally can incorporate any materials that are used in hot mixes. However, they are still considered inferior to hot asphalt mixes. This is due to three main concerns with respect to CAEMs, namely: high porosity of the compacted mixture, weak early life strength (caused mainly by the trapped water) and the long curing times (evaporation of water/volatiles content and setting of the emulsion) required to achieve maximum performance [1].

In general, CAEMs are simple to produce and suitable for; low to medium traffic conditions; works in remote areas; and small scale jobs (at numerous locations) such as reinstatement works. However, currently there is no universally accepted mix design method for CAEMs.

The hot mixes used for stiffness (ITSM) comparison were produced using the same materials with the cold mixes. Creep and fatigue comparison was done using data available from previous publication [2,3,4].

The CAEMs results presented in this paper were obtained using a simplified design procedure recommended by the author [5]. This simplified design

procedure is considered more practical. The target compacted mix porosity was five to ten percent [6] and a minimum stiffness value (ITSM) of 2000 MPa was set [7,8], that are suitable for low to medium trafficked roads.

The objective of the experiments was to evaluate and improve the performances of cold mixes and compared with hot mixes.

## AGGREGATE GRADATIONS FOR THE MIXES

The aggregate gradations of all the design mixes used in this investigation were based on Cooper's formula [9] as shown below:

$$P = \frac{(100 - F)(d^n - 0.075^n)}{D^n - 0.075^n} + F \quad (1)$$

where P is percent material passing sieve size d (mm), D maximum aggregate size (mm), F percent filler, and n an exponential value that dictates the concavity of the gradation line. The n value used was 0.45 which is an exponential factor that can be used producing a good aggregate packing. The value selected for D was 12 mm and F was equal to four percent which satisfies the allowable limits for filler content in Dense Asphalt [10]. Using Equation (1) above, the aggregate gradation obtained consist of 56.61% coarse fraction (retained 2.36mm), 39.39% fine fraction (2.36-0.075 mm), and four percent filler (passing 0.075mm), as shown in Figure 1. When plotted into a graph together with the upper and lower recommended specification limits (upper limit-

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UL, and lower limit-LL) specified by Nikolaidis [11] for comparison, the CAEMs aggregate grading chosen closely follows the lower limit of Nikolaidis grading.

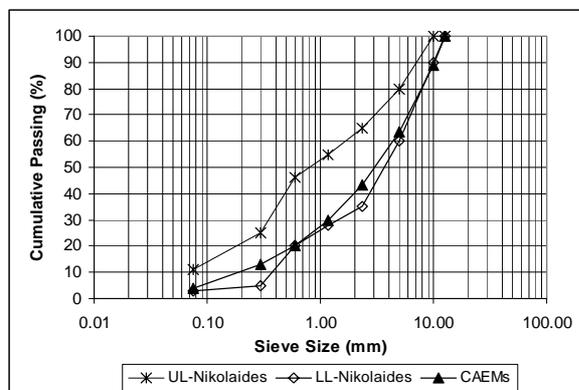


Figure 1. Aggregate Grading of CAEMs compared with Specification of Nikolaidis [8].

### Materials Used for The CAEMs

The coarse and fine aggregates used for the CAEMs and their properties are given in Table 1. The filler was fly ash from Eggborough power station with density 2.2 gram/cm<sup>3</sup>.

Table 1. Properties of the aggregate materials used for the CAEMs.

Properties	Limestone coarse aggregate	Crusher sand fine aggregates *	Specification [12, 13]
Aggregates Abrasion Value (%)	15.5	1.7	>10: unsuitable for surfacing
Aggregates Crushing Value (%)	25	14	<10: strong >25: weak
Aggregates Impact Value (%)	21	14	< 10: strong > 30: weak
Magnesium Sulfate Soundness Value (%)	94	96	Min: 75%
Density (gr/cm <sup>3</sup> )	2.65	2.59	≥2.5
Water Absorption (%)	1	0.90	<3

\* By-product of aggregate crushing

It can be seen in Table 1, the aggregates used are not suitable for surface courses in heavy trafficked roads. As CAEMs are suitable for low to medium trafficked road, hence the materials were incorporated.

The optimum residual asphalt content of the CAEMs was already previously determined at six percent [5]. The binder used for the CAEMs was a cationic asphalt emulsion (60 % asphalt content) with 100 pen. grade base asphalt obtained from Nynas Asphalts, UK. The specific gravity of the base asphalt was 1.02.

### Mixture Designation of The CAEMs

Depending on the material types incorporated, the CAEMs were designated as shown in Table 2.

Table 2. Mixture designation and composition of the CAEMs.

Name of mix	Coarse aggregates (56.61 %)	Fine Aggregates (39.39 %)	Filler (4 %)
CAEM	Limestone	Crusher sand	fly ash
CAEM+cement	Ditto	Ditto + (1-2) % cement by mass of aggregates	Ditto

In cases where an accelerated rate of strength gain desired, ordinary Portland cement in the amount of one to two percent (by mass of the aggregates) is commonly added into the mix.

### Mix Design, Compaction, and Curing Procedures for The CAEMs

The design procedure recommended by the author [5] overcomes the impractical requirement of the determination of optimum water content at compaction on site. It ensures that the porosity requirement is met; the retained stability is evaluated at optimum residual asphalt content only, which reduces the number of samples needed; and provides data on the ultimate strength of the CAEMs under full curing conditions.

Compaction of the CAEMs specimens was carried out using a Gyropac (Figure 2) compactor set at 240 kPa axial pressure (for 100 mm diameter samples) with an angle of gyration of 2°. The two compaction levels routinely used with this type of equipment are:

- Medium compaction level: 80 revolutions in the Gyropac, which is equivalent to the compaction effort generated when applying 50 blows each end using a Marshall hammer.
- Heavy compaction level: 120 revolutions in the Gyropac, which is equivalent to the compaction effort generated when applying 75 blows each end using a Marshall hammer.

Following several compaction trials with the Gyropac it was found that in order to achieve the target air void content of five to ten percent the compaction level had to be increased by up to two times the heavy compaction level routinely specified. This higher compaction level was subsequently referred to as extra heavy compaction [5].

Laboratory curing of the CAEMs were carried out in an oven set at 40°C. Full curing conditions were achieved when the specimens following repeated weighing, maintained a constant mass at 40°C. Typically, full curing conditions were achieved within 18 to 21 days for samples with porosity values in the range of eight to nine percent.

### Mechanical Properties Tested

The mechanical properties tested were indirect tensile stiffness modulus (ITSM) at 20 °C [14], dynamic

creep at 40 °C, and fatigue at 20 °C [15]. The specimens were tested using a universal Materials Testing Apparatus (MATTA), as shown in Figures 3, 4, and 5. Three samples were tested for each type of mix and the results were averaged.

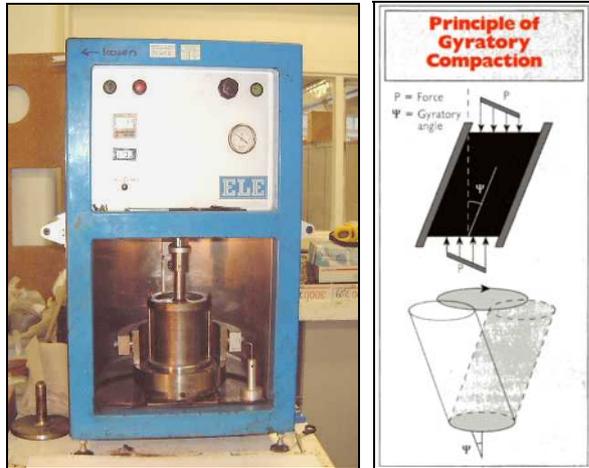


Figure 2. Gyropac Compactor and Principle of Gyratory Compaction.

### Stiffness Comparison of The CAEMs to Hot Mixes (100 pen. grade)

The stiffness (ITSM) performances of the CAEMs were compared to hot mixes composed of the same materials. The hot mixes were also of six percent asphalt content (100 pen. grade). The mixing and compaction temperatures were set at 140°C and 125°C, respectively [16].

Three hot mix samples were compacted in medium compaction effort and three others were in heavy compaction. The results were averaged and presented in Table 3.

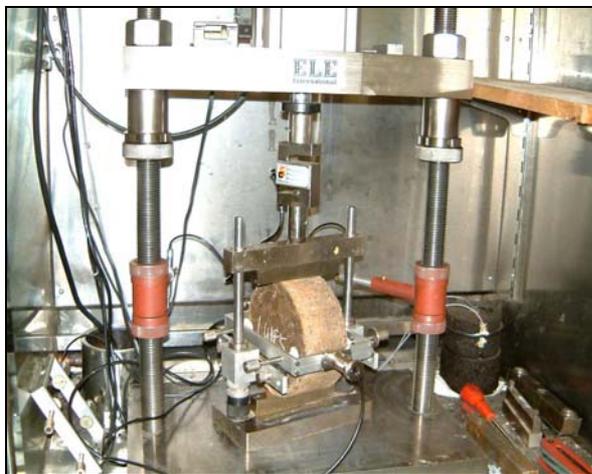


Figure 3. Configuration of Indirect Tensile Stiffness Modulus (ITSM) Test.



Figure 4. Configuration of Dynamic Creep Test.



Figure 5. Configuration of Fatigue Test.

Table 3. Properties of the CAEMs compared to Hot Mixes.

Mixture type	Compaction effort	Porosity (%)	ITSM (MPa)
CAEM	2 × heavy compaction	9.7	2275 (full curing)
CAEM + 1% cement *	2 × heavy compaction	9.4	3378 (full curing)
CAEM + 2% cement *	2 × heavy compaction	9.2	4970 (full curing)
100pen. Hot Mix	Medium compaction	4.7	2150
100pen. Hot Mix	Heavy compaction	3.4	2520

\* by mass of aggregates

Referring to Table 3, in order to meet the target porosity range of five to ten percent, the CAEMs required two times the heavy compaction level. Even at this compaction level, only porosity values in the range of eight to nine percent could be achieved. This is because the CAEMs become stiffer as more bitumen droplet of the emulsion set (coalesce) during compaction.

The stiffness of the CAEM specimens, even without the addition of any cement, at full curing conditions did meet the minimum stiffness target of 2000 MPa. The addition of one to two percent cement by mass of aggregates significantly increased the resultant stiffness. The results shown in Table 3 also show that the porosity of the CAEMs was somewhat higher than the hot mixes, however the stiffness was comparable. This is thought to be due to the effect of chemical formulation of the emulsion.

Compared to CAEMs, hot asphalt mixes when mixed and compacted at the correct temperatures normally possess better coating and workability. This is evident from the porosity and compaction effort results shown in Table 3, where the hot mixes give lower porosity values at lower compaction efforts.

### CREEP PERFORMANCE OF THE CAEMs

Dynamic creep tests were carried at the following test conditions: Pulse width 1000 millisecond (ms), Pulse Period 2000 ms, Test Termination Strain 100000 micro-strain ( $\mu\text{s}$ ), Terminal Pulse Count 3600 pulses, Conditioning stress 10kPa, Test loading stress 100 kPa, conditioning time 15 minutes, Pre-load rest time two minutes, recovery time two minutes. The tests were carried out at 40 °C.

#### Creep Performance of CAEMs Compared to Hot Mixes

The creep performances of the CAEMs (number of load cycles vs. cumulative strain) are shown in Figure 6. As is generally the case for creep behavior, the creep curve can be divided into three main regions; the primary creep region where the strain rate decreases with the number of load cycles applied; the secondary creep region where the strain rate is almost constant, otherwise known as the steady state strain rate; and the tertiary creep region where the strain rate increases rapidly up to failure. The steady state strain rates, or creep slope values are shown in Figures 6, and 7, and Table 4.

The creep results were compared with the available data of a Dense Asphalt Macadam (DBM) 20mm max aggregate size hot mixes with five percent optimum 100 pen asphalt content, and porosity range from 2.2 – 8.6 %. Gibb [2] found their creep strain with lower and upper limit are as shown in Figures 6 and 7.

Creep slopes were derived from the linear portion of Figure 6 (as shown in Figure 7). By utilizing linear analysis (trend line), the equation and creep slopes (the coefficient of variable x), are given in Table 4.

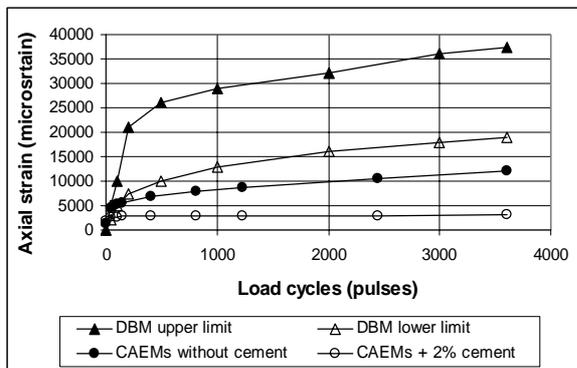


Figure 6. CAEMs Dynamic Creep Test Results at 40°C, Compared to Hot Mixes

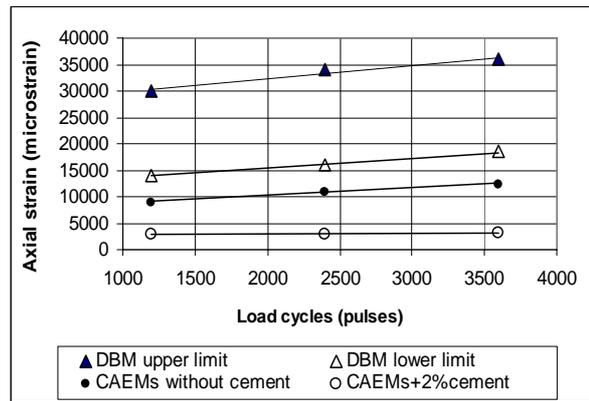


Figure 7. Creep Slopes derived from the linear portion of Figure 6.

Table 4. Creep Slope Data (Referring to Figures 6 and 7).

Mixture	Test temp. (°C)	Linear Regression Equations and R <sup>2</sup>	Slope of Creep Curve ( $\mu\text{e}/\text{pulse}$ )
20mm max agg. size DBM100pen upper limit [2]	40	$y = 1.875x + 11667$ $R^2 = 0.9959$	1.875
20mm max agg. size DBM100pen lower limit [2]	40	$y = 2.5x + 27333$ $R^2 = 0.9643$	2.5
CAEM	40	$y = 1.4167x + 7400$ $R^2 = 0.9897$	1.4167
CAEM + 2% cement by mass of aggregates [5]	40	$y = 0.0396x + 2980$ $R^2 = 0.9402$	0.0396

Referring to Table 3, it revealed that although cold mixes generally of higher porosity, their stiffness were higher than hot mixes. This is also in phase with the creep slopes of the cold mixes in Table 4, where the cold mixes at full curing gave lower slopes (indicates better resistance to deformation) compared to hot mixes, as shown in Figure 7. This condition may have not yet fully understood as more results are needed for comparison. However, it is thought that the chemical formulation of the asphalt emulsion and its affinity with the aggregates play some roles, where at full curing condition, asphalt emulsion mixes perform at least comparable or even better than hot mixes.

Considering the creep slopes of the cold mixes shown in Table 4, and referring to Table 5, it is confirmed that cold mixes are suitable for low to medium trafficked road.

Table 5. Typical laboratory determined minimum dynamic creep slope values [17].

Average annual pavement temperature (°C)	Heavy Traffic > 10 <sup>6</sup> ESA	Medium Traffic 5×10 <sup>5</sup> to 10 <sup>6</sup> ESA	Light Traffic < 5×10 <sup>5</sup> ESA
> 30	< 0.5	0.5 - 3	> 3 - 6
20 - 30	< 1	1 - 6	> 6 - 10
10 - 20	< 2	2 - 10	Not Applicable

**Creep Stiffness of The Mix ( $S_{mix}$ )**

The  $S_{mix}$  value is an additional indicative of the resistance to permanent axial deformation. For asphalt specimens the  $S_{mix}$  is basically obtained from the ratio of applied stress (100 kPa) to the cumulative compressive strain at a defined temperature and time of loading, as can be seen in Figure 8. Mixes with lower stiffness (ITSM) are common to undergo higher deformation, hence it is logical to  $S_{mix}$  values. Figure 8 is in line with the trend in Figure 6.

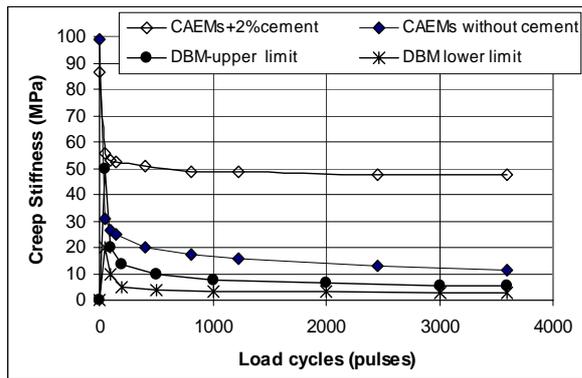


Figure 8. Dynamic Creep Stiffness of The Mixes.

**Fatigue Performances**

Fatigue is a phenomenon of fracture/failure under repeated loading. Fatigue test results can be expressed as a relation of number of loading (pulses) to strain at failure. The fatigue performances of the cold mixes were compared with a 12mm max aggregate size of asphalt concrete mixes (AC) of 100 pen asphalt with five percent porosity [3], and a 20mm max aggregate size of DBM 100pen [4] with porosity of 5.1 %. Both hot mixes were at optimum asphalt content. The fatigue lines are shown in Figure 9 (in a log-log scale).

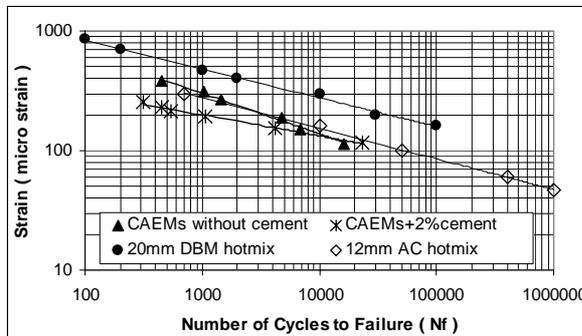


Figure 9. CAEMs Fatigue Performance Compared to Hotmixes

The fatigue line equations and coefficient correlation  $R^2$  from fatigue tests are presented in Table 6.

Referring to Table 6 and Figure 9, it can be clearly seen that the fatigue lines of the CAEMs with two

percent added cement were flatter than the cold mix without cement. At a projected life to failure ( $N_f$ ) of one million load (pulse) cycles, the CAEMs incorporating two percent cement can withstand 59 micro strain, about twice the strain (deflection) of the cold mix without cement. Similarly, the number of cycles to failure ( $N_f$ ) of the CAEMs incorporating cement at a relatively low deflection value of 100 micro-strains ( $4.84 \times 10^4$  cycles) were also much higher than that of the cold mixture without cement. This indicates that incorporating cement significantly improves the performance of CAEMs, in particular at low strain levels, for example, when acting as part of a well designed pavement structure.

**Table 6. Fatigue Lines Equations (exponential regression line/trend line) and Coefficient of Correlation ( $R^2$ )**

Mixture	Equation based on Strain (Figure 9)	Equation based on number of cycles to failure*	$\epsilon_i$ ( $\mu\epsilon$ ) at $N_f = 10^6$ cycles	$N_f$ (cycles) at $\epsilon = 100 \mu\epsilon$
CAEMs without cement [5]	$\epsilon = 3152.2 \times N_f^{-0.3397}$ $R^2 = 0.9898$	$N_f = 2.0 \times 10^{10} \epsilon^{-2.91}$ $R^2 = 0.9898$	29	$3.03 \times 10^4$
CAEMs + 2% cement [5]	$\epsilon = 679.37 \times N_f^{-0.1774}$ $R^2 = 0.9899$	$N_f = 7.0 \times 10^{15} \epsilon^{-5.58}$ $R^2 = 0.9899$	59	$4.84 \times 10^4$
20mm DBM hot (100 pen.) [4]	$\epsilon = 2532.1 \times N_f^{-0.2406}$ $R^2 = 0.9950$	$N_f = 1.0 \times 10^{14} \epsilon^{-4.14}$ $R^2 = 0.9950$	91	$5.25 \times 10^5$
12mm A.C. hot (100 pen.) [3]	$\epsilon = 1638.4 \times N_f^{-0.2567}$ $R^2 = 0.9991$	$N_f = 3.0 \times 10^{12} \epsilon^{-3.89}$ $R^2 = 0.9991$	47	$4.98 \times 10^4$

\* Based on data as in Figure 9, but the strain is plotted as the x-axis and the load cycles are plotted as the y-axis.

However, when compared with 14mm AC 100pen hot mixes, the fatigue performance of the cold mixes with added two percent cement were relatively comparable. But without cement the cold mixes were inferior. This is logical, in particular when considering the porosity values of the CAEMs which in general were much higher than the hot mixes. The 20mm DBM-100pen hot mixes had the best fatigue performance as it contained the largest maximum aggregate size (20mm).

The fatigue results above should have been affected by the porosity of the mixes, where the porosity of the CAEMs were almost twice of the hot mixes.

As fatigue is a parameter among other parameters for evaluating the performance of asphalt mixes, it is possible that one mixture perform better in one parameter but inferior in others. This could only be explained by the lack of repeatability of test results between different investigators.

**CONCLUSIONS**

The main conclusions drawn from this investigation are as follows:

1. Cold asphalt emulsion mixes (CAEMs) when properly designed and at full curing condition, even without the addition of cement were comparable in stiffness (ITSM) to hot mixes (of equivalent grade asphalt), although the porosity values were generally higher than in hot mixes. This is likely due to the effect of the quality of asphalt emulsion.
2. The addition of one to two percent cement by mass of aggregates into cold asphalt emulsion mixes significantly improves the overall mechanical performances of the CAEMs.
3. The application of heavier compaction level is inevitable in cold mixes, as the emulsion set (the bitumen droplets of the emulsion coalesce) hence the mixes stiffen during compaction.

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