Characterisation of high-performance cold bitumen emulsion mixtures for surface courses

Ahmed I. Nassar[a*], Mahmoud Khashaa Mohammed[b], Nicholas Thom[a] & Tony Parry[a]

[a]Nottingham Transportation Engineering Centre, Department of Civil Engineering, Faculty of Engineering, University of Nottingham, University Park, Nottingham NG7 2RD, UK

[b]Faculty of Engineering, Civil Engineering Department, University of Anbar, Anbar Governorate, Iraq

* Corresponding author. Tel.: +44 (0) 115 9 513 953; fax: +44 (0) 115 9 513 909.

E-mail address: evxan1@nottingham.ac.uk, ah.nassar@yahoo.com

Abstract:

Cold bitumen emulsion mixture (CBEM) is not yet widely used as a surface courses around the world. In this study, 0/14 mm size dense graded surface course CBEMs have been investigated. The mechanical performance was evaluated in term s of stiffness modulus over 3 months and resistance to permanent deformation under three different stress levels (100, 200, 300kPa) while durability evaluation was carried out in terms of resistance to moisture and frost damage. The study has also investigated the incorporation of low cement content (1%) with relatively sustainable by-product fillers, namely ground granulated blast-furnace slag (GGBS) and fly ash (FA) type 450-S on both mechanical and durability performance. A comparison has been carried out between the low and high cement content CBEM, as well as with

respect to corresponding hot mix asphalt (HMA). The results revealed that the incorporation of GGBS and FA in CBEMs leads to superior performance, similar to CBEMs treated with high cement content and comparable to an equivalent HMA. Furthermore, GGBS replacement exhibited better performance than that of FA replacement. The findings suggest that the new sustainable types of CBEM can be developed for using as a surface layer for medium to heavy trafficked roads.

Keywords: Cold Bitumen Emulsion Mixtures; Active filler; Surface course; Stiffness modulus; Repeated load axial test; Durability

1. Introduction

In recent years, the construction of roads using cold asphalt mixes (CAMs) has gained increasing interest around the world. For example, the annual production of CAMs is 1.5 million tonnes in France and 2 million tonnes in Turkey (Gómez-Meijide and Pérez 2014). However, in the UK, the use of CAMs is limited to base and sub-base courses of structural layers (Needham 1996, Khalid and Monney 2009, Thanaya *et al.* 2009). There is a significant need to carry out an intensive scientific research in order to develop CAMs, more precisely cold bitumen emulsion mixtures (CBEMs), for use as a surface course (Eckmann *et al.* 2004). This demands novel and sustainable CBEM products. The properties of these novel mixtures should be similar to conventional hot mix asphalt (HMAs) in order to justify their use as a surface course. CBEMs are known and accepted products that save resources and energy consumption, giving environmental protection with low pollution (Nikolaides 1994). However, CBEMs have several drawbacks that make their performance inferior as compared to HMAs (Thanaya 2003, Liebenberg and Visser 2004). The relatively wet and cold weather in the United Kingdom does not favour the emulsion curing process, and thus, additionally limits the use of the CBEM.

In the past, different attempts have been made to investigate and to enhance the performance of CAMs using hydraulic binder such as cement and lime. The most extensively used hydraulic binders are ordinary Portland cement (OPC) and hydrated lime (Niazi and Jalili 2009). The addition of OPC to CBEMs dates back to 1970. A series of three studies were carried out by Terrell and Wang (1971), Schmidt et al. (1973) and Head (1974) to improve the resilient modulus of emulsion treated mixes using cement. The results showed that the rate of development of this property was significantly accelerated by the addition of up to 3% cement in the early stages of curing and the increase in resilient modulus reached up to 200% depending

on emulsion type. Needham (1996) claimed that the incorporation of cement into CBEMs can increase: stiffness modulus, resistance to permanent deformation, resistance to fatigue cracking (at initial strains below 200 microstrain) and improve resistance to moisture damage.

A laboratory study was conducted by Li *et al.* (1998) to evaluate the mechanical properties of cement-asphalt emulsion composite (CAEC). This study indicated that combining cement and emulsified asphalt improves material performances by gaining the beneficial properties of both cement concrete and asphalt concrete. The results showed longer fatigue life and lower temperature susceptibility of cement concrete, and higher toughness and flexibility of asphalt concrete.

Another study was conducted by Oruc *et al.* (2007) to evaluate the mechanical properties of emulsified asphalt mixtures having 0% to 6% OPC. The results also showed a significant enhancement with high additions of OPC. Furthermore, the authors recommended that the cement-modified asphalt emulsion mixes could be used as a pavement surface layer.

Thanaya *et al.* (2009) concluded that the addition of 1% to 2% rapid-setting cement increases the strength gain significantly and improves the other mechanical properties of the modified cold mixes such as resistance to rutting and fatigue distresses at early age. A study implemented by Wang and Sha (2010) also pointed out that the rise of cement and mineral filler fineness has a positive impact on the micro-hardness of the interface of aggregate and cement emulsion mortar.

Therefore, the role of the cement is to control the breaking behaviour of the bitumen emulsion, and to increase the early mixture strength and stiffness by binding excessive water released by the emulsion. Additional cement reduces the negative influence of the released water and improves the adhesion of the binder to the aggregate, which might positively affect the water

sensitivity of the mixture in general (Needham 1996, Lu *et al.* 2009, Wang and Sha 2010, Wang *et al.* 2013, Miljković and Radenberg 2014). The presence of cement also increases the pH value of the aqueous phase of the emulsion, and thus, accelerates its breaking. However, the use of relatively high cement content for CBEMs increases their cost and would contribute to increasing cement demand worldwide. The emission of CO_2 to the atmosphere during the production of cement is about (5-7)% of the total CO_2 emission from different sources (Humphreys and Mahasenan 2002, Benhelal *et al.* 2013). Therefore, it is worth reducing the amount of cement in CBEMs and for this reason a relatively low cement content was adopted in this research (1.0%). The most sensible way to achieve this is to use by-product filler (manufacturing wastes) as supplementary cementitious materials. A significant quantity of these materials produced in the UK. Thus, the annual production of granulated blast-furnace slag (GGBS) and fly ash (FA) are estimated to be 2.2 and 6 million tonnes, respectively. However, limited studies have been conducted to investigate the use of by-product materials to enhance CBEM properties. Ellis *et al.* (2004) have studied a range of mixtures of recycled aggregate composed of road base layer, concrete demolition waste and brick sand. These aggregates were stabilized using bitumen emulsion and GGBS. They stated that the addition of GGBS to bitumen emulsion mixtures can provide better mechanical performance than untreated mixtures, especially in the long term under high humidity curing conditions.

Al-Busaltan *et al.* (2012) confirmed the enhancement of close graded CBEM to a stage where its mechanical properties are comparable to those of traditional asphalt concrete mixtures. The improvement was due to replacement of the conventional mineral filler with a domestic fly ash. Al-Hdabi *et al.* (2014) showed a significant improvement in cold rolled asphalt by incorporating a biomass fly ash with cement. A comparison study between coal ash and OPC in CBEM was carried out by (Modarres and Ayar 2016). The result revealed that the application

of coal waste powder improved the mechanical properties of cold recycled asphalt material, but it could not achieve a positive impact on moisture damage resistance. Based on these comparisons, coal waste powder and its ash were found to have comparable effects to OPC.

Promotion of CBEMs and their performance has recently been a significant aim of many researchers using high OPC content (García *et al.* 2013, Fang *et al.* 2014). In contrast, the aim of this study is to improve the mechanical properties and the durability of CBEMs with low cement content and different by-product materials, namely FA and GGBS. To achieve this aim, the mechanical properties have been assessed by both the indirect tensile stiffness modulus test (ITSM) and the Repeated Load Axial Test (RLAT). The durability assessment was evaluated by moisture susceptibility and freeze-thaw tests.

2. Material and Testing Program

2.1. Material Characteristics

The aggregate used in this study was crushed limestone. The gradation of aggregate was within the limits of 0/14 mm size dense graded surface course, according to BS 4787-1. The selection was in order to ensure an appropriate interlock between the aggregate particles in the mixtures (European Committee for Standarization 2006). The amount of mineral filler (passing sieve 0.063 mm) was 5% of the total weight of aggregate. The gradation of the aggregate is shown in Figure 1, and its physical properties are listed in Table 1.
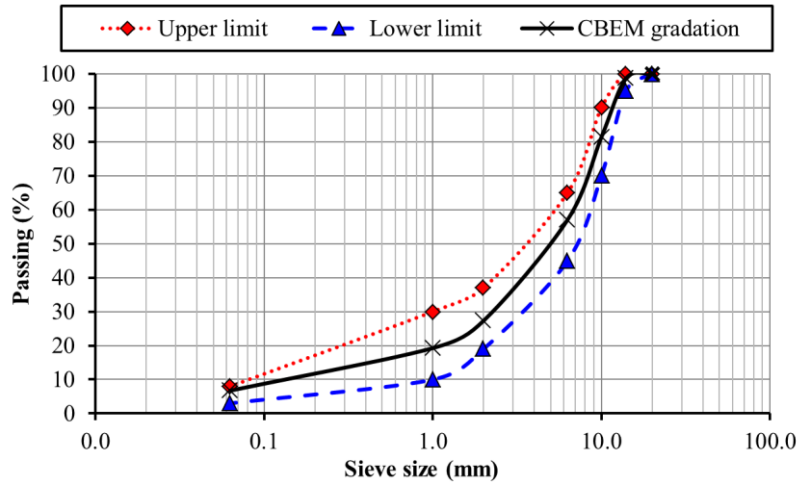
Figure 1 Limestone aggregate gradation of 0/14 mm size close graded surface course according to BS 4787-1.

Table 1 Physical characteristics of limestone aggregate*

Properties	Value	Standard
Density- Oven Dried	2.68 g/cm^3	EN 1097-6
Density- Saturated Surface Dried	2.69 g/cm^3	EN 1097-6
Density- Apparent	2.70 g/cm^3	EN 1097-6
Water Absorption	0.4 %	EN 1097-6
Aggregate Abrasion Value (AAV)	11.0	EN 1097-8
Polished Stone Value (PSV)	31	EN 1097-8
Los Angeles Coefficient (LA)	28	EN 1097-2

* This information was provided by aggregate supplier.

A cationic slow setting bituminous emulsion, C60B5, was used to manufacture the CBEMs. The high stability and high adhesion of cationic emulsion was the reason this type of emulsion was selected, as recommended by Nikolaides (1994) and Thanaya (2003). 40/60 penetration grade bitumen was used in emulsion production. The other relevant properties of the selected bituminous emulsion are shown in Table 2.

Table 2 Bitumen emulsion properties

Property	Value	Standard
Appearance	Black to dark brown liquid	
Breaking Behaviour	> 170	EN 13075-1
Softening Point (°C)	52	EN 1427
Viscosity - Efflux time 2mm - 40°C (s)	15-70	EN 12846
Adhesiveness	>90	EN13614
Particle surface electric charge	Positive	EN 1430
Bitumen content (%)	60	EN 1428
Penetration (dmm)	47	EN 1426
Density (g/cm³)	1.016	

For comparison purposes, a hot mix asphalt (HMA) has been included in the study. This mix contained the same aggregate type, gradation and base binder (40/60) as used in the CBEM. The bitumen content in the HMA was 4.9% as recommended by European Committee for Standarization (2006).

Four types of filler material were used in this study. Natural limestone filler (LF) was used as conventional filler and Ordinary Portland cement (OPC) CEM I 42.5N was utilized as a hydraulic binder. Besides, a combination of OPC, FA type 450-S, (class F) according to ASTM C-618, and GGBS obtained from Cemex and Hanson respectively, were used for manufacturing the sustainable type of CBEM specimens.

FA is a fine ash precipitated from the exhaust gases during coal combustion at power stations. In the current research, Fly ash type 450-S produced by Cemex Company was used. This FA contains approximately 50% silica and 26% alumina. This mineral filler could be classified as Class F according to the American Society of Testing Material ASTM C-618. Furthermore, GBBS is a by-product resulting from the grinding of blast furnace slag. The GGBS used in this

study contains 40% lime, 35% silica and 11% alumina. Both FA and GGBS, in the presence of cement, can enhance formation of new cement hydration products due to their chemical reactivity with the Calcium Hydroxide $Ca(OH)_2$ in the hydrated cement.

Similar materials were used by Mohammed *et al.* (2013) to investigate the hydration, microstructure and the durability of a sustainable type of concrete.

A detailed characterization was carried out to investigate the chemical and physical properties of the selected fillers. The chemical composition of fillers (major oxides) were analysed by energy dispersive X-ray spectroscopy (EDX). The analysis is conducted by applying X-ray to the sample and then analysing the re-emitted characteristic fluorescent X-ray. The results are presented in Table 3.

Table 3 Chemical compositions of fillers

| Formula | Alias | Types of filler | | | |
		FA	GGBS	LF	OPC
Na_2O	Sodium oxide	1.27	0.28	--	0.56
MgO	Magnesium oxide	1.76	6.89	--	2.04
Al_2O_3	Aluminium oxide	25.14	11.21	--	4.11
SiO_2	Silicon dioxide	51.32	35.65	1.97	19.84
SO_3	Sulfur trioxide	1.90	2.43	--	5.41
K_2O	Potassium oxide	4.24	0.64	--	1.06
CaO	Calcium oxide	2.57	41.42	98.03	64.35
TiO_2	Titanium dioxide	1.29	0.63	--	0.25
Fe_2O_3	Iron oxide	9.77	0.26	--	2.39
P_2O_5	Phosphorus hemi-pentoxide	0.74	--	--	--
MnO	Manganous oxide	--	0.60	--	--

The particle size distribution was carried out by Beckmen Coulter Laser diffraction particle size analyser (see Figure 2). Further, scanning electron microscopy (SEM) was used for determining the fillers' morphology as shown in Figure 3. SEM analysis was implemented under a resolution of 3-4 nm and an accelerated voltage of 15 kV.
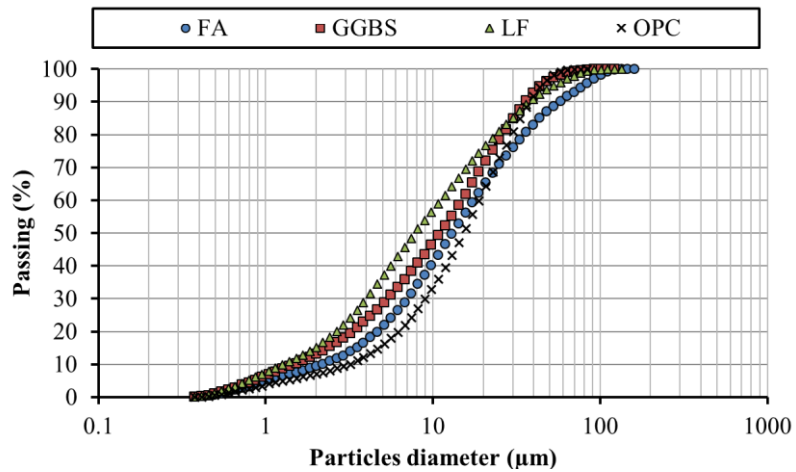

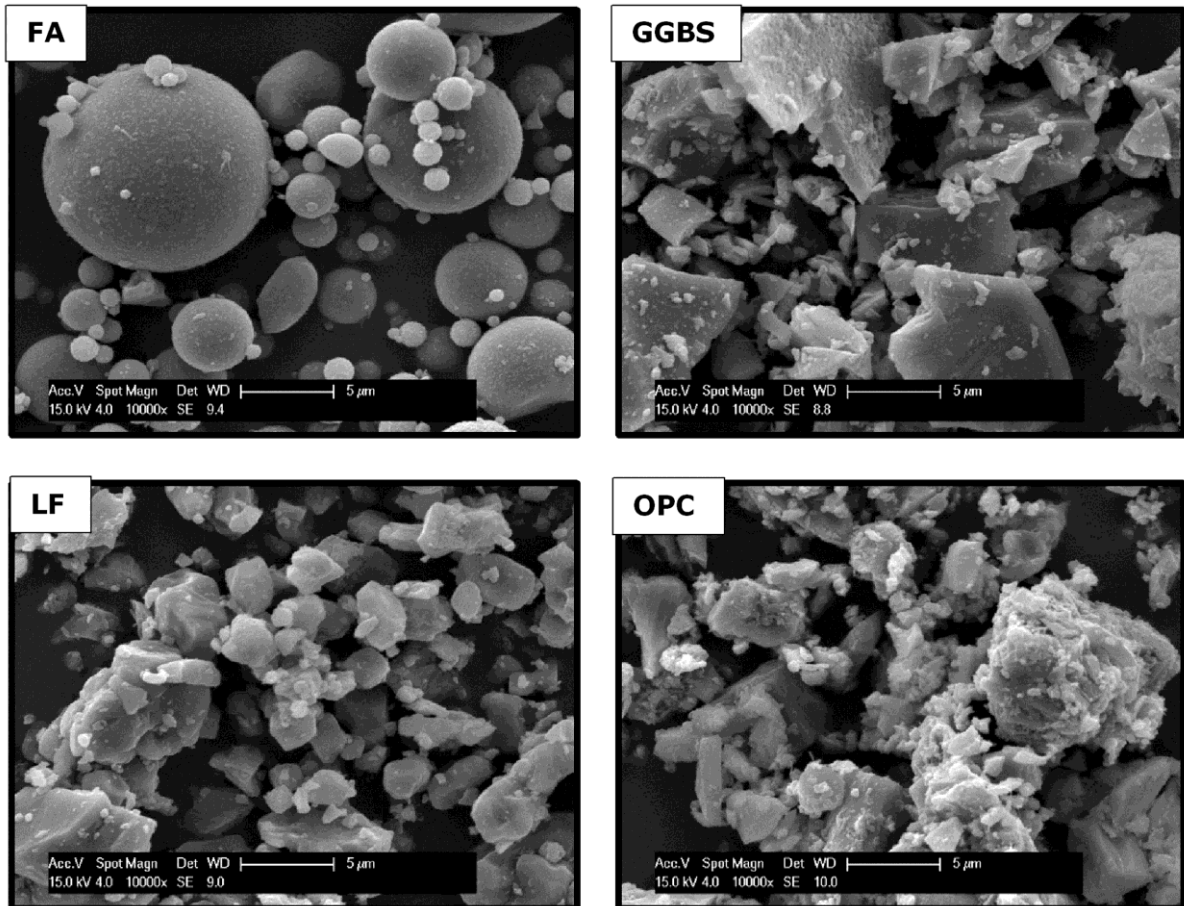**Figure 2 Particle size distribution of fillers.**

Figure 3 Morphology of fillers.

2.2. Mix Proportions and Sample Preparation:

The proportions of the control CBEM were statistically optimized using the response surface method (RSM). Generally, RSM is a mathematical and statistical model which can be used for detecting the factor settings to optimize the average response values. Particularly in mix designation of CBEM, RSM was used as an optimization technique to adjust the mixture parameters (bitumen emulsion and pre-wetting water contents) to achieve acceptable mechanical strength and suitable volumetric properties. Based on this technique, the optimum bitumen emulsion content was 6.75% and the optimum pre-wetting water content was 2.12% of the total weight of aggregate for the reference mix. The complete details regarding the mix proportions based on RSM are described in a previous research work (Nassar *et al.* 2016).

11

The same mixture proportions were used to prepare four alternative CBEMs with cement and other fillers see Table 4.

Table 4 CBEM types and the designation of fillers combination

Mixture type	Filler content by mass (%)		
	LF	FA/GGBS	OPC
LF-CBEM (Control mix)	100	0	0
Low OPC-CBEM	80	0	20
High OPC-CBEM	0	0	100
GGBS-CBEM	0	80	20
FA-CBEM	0	80	20

The total amount of fillers was fixed at 5% by total weight of the aggregate. Marshall specimens with thickness (55 to 60) mm were prepared for all CBEMs. Mixing was carried out using a Sun and Planet mixer. Thereafter, impact compaction (Marshall hammer) was utilized to compact the specimens; following a pilot study 75 blows were applied to each face. Whilst it is recognized that the compaction method may influence CBEM properties (Miljković and Radenberg 2016). The Marshall compaction was selected due to it is convince to produce a suitably dense mixture. After compaction, the curing protocol followed was such that the specimens were left in the moulds (in a sealed condition) after compaction for 24hrs after which they were extruded. Specimens were conditioned in a thermostatically controlled air chamber at 20°C. This curing temperature was selected as the most conservative approximation to simulate actual performance of CBEM on site as well as to avoid any early ageing of the binder (Serfass *et al.* 2004, Khalid and Monney 2009, Ojum *et al.* 2014).

3. Experimental Program:

3.1. Indirect Tensile Stiffness Modulus (ITSM)

The curing trends of CBEMs were developed by monitoring weight loss and stiffness gain over a period of time. The non-destructive stiffness test, ITSM, was selected for assessing the stiffness of these CBEMs over a period of 3 months. The ITSM, as shown in Figure 4, was performed in order to carry out the test on the same set of specimens to nullify variability in the mixtures and to derive reliable results for stiffness evolution.
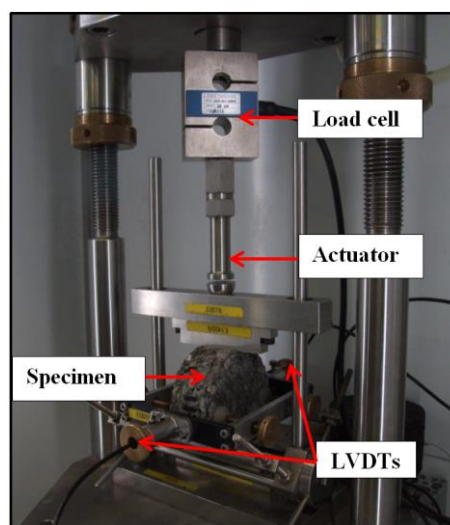

Figure 4 Configuration of ITSM test.

Stiffness modulus is considered as an indicator for the structural behaviour of mixtures because it is related to the capacity of the material to distribute traffic loads. Following BS EN 12697-26, an impulsive load was applied with a rise-time of 124 ms, to achieve a target horizontal deformation of 7 ± 2 μm. Ten conditioning pulses were applied to the specimens followed by five test pulses. The measurements were repeated along two diameters and the average stiffness values were calculated (European Committee for Standarization 2012). For HMA, the specimens were conditioned and tested at 20°C. The ITSM was performed at 3, 5, 7, 14, 28, 45 and 84 days. Four specimens per mix were tested under the same conditions.

3.2.Repeated Load Axial Test (RLAT)

The Repeated Load Axial Test is the most widely used standard mechanical test in the UK for assessing the permanent deformation characteristics of bituminous mixtures. The test applies a repeated pulse load to simulate the traffic and measures the permanent deformation after each repeated load. The protocol for the RLAT test was performed based on BS EN 12697-25. Table 5 and Figure 5 show the test configuration of the RLAT (European Committee for Standarization 2005).

Table 5 RLAT test configuration based on BS EN 12697-25

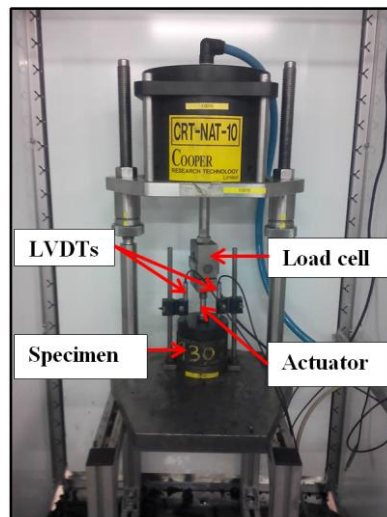| Item	Range
Specimen diameter	100±2 mm
Conditioning stress	10kPa
Conditioning period	600 s
Test stress	100kPa, 200kPa, 300kPa
Test Duration	3600 cycles
Test Cycle	Square wave pulse 1s on, 1s off
Specimen thickness	40-80 mm
Test temperature	40°C

Figure 5 Configuration of RLAT test.

After compaction, the specimens were cured at 20°C for 28 days; thereafter they were cured in a forced draft oven for a further of 7 days at 40°C. This curing protocol was selected to make sure that the fully curing condition was achieved as recommended by Needham (1996) and Oke (2011). The two faces of the specimen were coated with a thin layer of silicone grease with graphite powder before running the test. Graphite powder is applied in order to eliminate the influence of unevenness of the specimen face on the test results.

3.3.Durability Evaluation

Durability is a feature directly related to the effect of environmental condition on the performance of asphalt mixtures during the service life. The durability of CBEMs has been evaluated against both the moisture and frost damage. This is in order to present a wide overview regarding the performance of CBEMs in warm and cold climates. Both damage modes are potentially serious problems in a wet and cold weather. Moisture and frost damage were evaluated based on BS EN 12697-23 and ASHTOO T283, respectively. Although (Al-Busaltan et al. 2012, Al-Hdabi et al. 2014) used different curing regimes before applying the water damage protocol (3day at 40°C), it was found to be very difficult to apply the damage protocol before 7days because the specimens of the control mix exhibited very low strength at early age. At this age, after 7days, it is considered that all the mixtures will have developed sufficient strength to allow testing for resistance to water and frost damage. The tests were carried out using three sets of specimens:

- The first set (unconditioned/dry) was tested after curing for 7 days at 20°C;
- The second set (first conditioned group/wet) was cured at 20°C for 7 days, after which the specimens were subjected to vacuum saturation for 30min (6.75kPa) before being soaked in a water bath for 3 days at 40°C and finally soaked for 2hrs at 20°C;

15

- The third set (second conditioned group/Freeze-thaw) was also cured at 20°C for 7 days, after which the specimens were subjected to a vacuum for 10 to 30min (13-67kPa) until they reached at saturation level between 55% and 80%.The specimens were then wrapped in plastic bags and exposed to freeze-thaw cycles. The cycle consisted of freezing at − 18°C for 16hrs followed by soaking in a water bath at 60°C for 24hrs and finally soaked for 2hrs at 20°C.

Durability of mixtures can be defined as the loss of strength in a mixture due to the effects of the exposure condition. The evaluation of durability was measured as indirect tensile strength ratio (ITSR) as defined in equation (1).

$$ITSR = \frac{ITS_{conditioned}}{ITS_{unconditioned}} \times 100 \tag{1}$$

$ITS_{conditioned}$ is the average indirect tensile strength of conditioned specimens; $ITS_{unconditioned}$ is the average indirect tensile strength of unconditioned specimens.

The ITS test involved applying diametric compression with a constant deformation rate of (50 ± 2) mm/min to the samples between two loading strips, which creates tensile stresses along the vertical diametral plane causing a splitting failure. The test was conducted at 20°C using Instron test equipment.

4. Results and Discussion

4.1.Indirect Stiffness Modulus:

Figure 6 shows the stiffness gain over time for different CBEMs. It is known that the monitoring of CBEM properties over the curing period is essential in order to understand the performance properly. A considerable increase in modulus was found when all or part of the conventional filler in LF-CBEM was replaced by other active fillers. It has been already established that the stiffness of CBEM is highly reliant on the removal of moisture from the

mixture as well as the breaking of bitumen emulsion (Needham 1996). However, incorporating fillers such as GGBS and FA produced contradictory trends by retaining a relatively high amount of water maintained inside the mixture due to: (1) the water physically adsorbed on the surface of aggregate/filler, (2) the water trapped in the closed pores within the bitumen and (3) the water bounded by the cement paste or cement paste plus active filler. The main feature of this water is that it cannot easily evaporate. In the current research, these three types of water will be termed as the trapped water. From other side, the evaporated water has been quantified by (1) tracking the mass loss of CBEMs specimens over the curing period and (2) further drying of CBEMs specimens for 7days at 40 ℃ in order to measure any residual evaporated water inside the mixture. Finally, the trapped water was calculated by subtracting the evaporated water from the initial water content present in the CBEMs specimens. In Figure 7, the trapped water increases with the presence of FA and GGBS to about 38.5% and 53.4%, respectively, and the trapped water in OPC-CBEM reaches a maximum value of 56.7%, whereas LF-CBEM trapped only 25.0%. It is clearly deduced that the amount of trapped water in by-product treated mixes is quite high as high OPC-CBEM, indicating the role of the FA and GGBS in maintaining trapped water inside the mixture to be used for enhancing the hydration process with time and producing new hydration products due to filler reactivity.
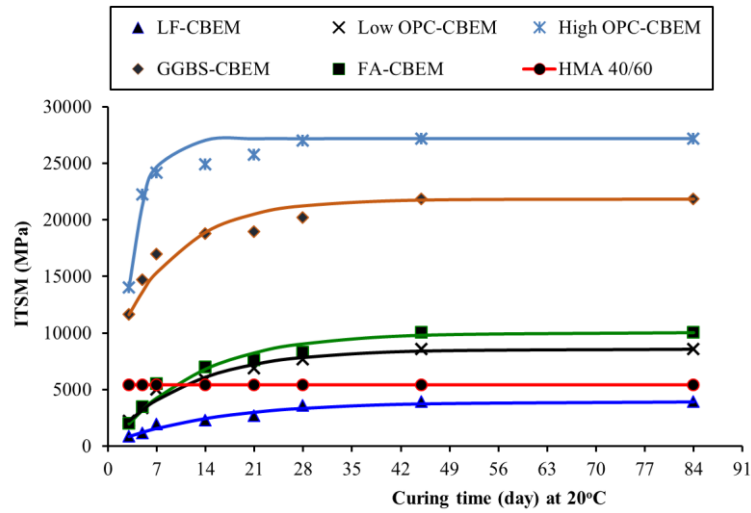
Figure 6 The stiffness modulus of studied mixtures over the curing period.

It is known that the use of GGBS and FA has a positive effect on reducing the amount of the Ca(OH)$_2$ (undesirable cement hydration products) in the mix. At the end of the reaction of the GGBS and FA, and Ca(OH)$_2$, new hydration products, such as C–S–H gel, is formed (Oner and Akyuz 2007).

Table 6 presents model (2) parameters fitting, which has been used to describe the increase of stiffness in CAM (Bocci *et al.* 2011); test fit curves are shown in Figure 6.

$$S_t = S_{max} - (S_{max} - S_o).e^{-b.(t-t_o)} \tag{2}$$

S_t: is the modulus at a specific curing temperature (MPa); t is the time (day); S_{max}: is the maximum (long-term) modulus (MPa); S_o: is the initial modulus (MPa); b is a parameter indicating the rate of increase in stiffness.

Table 6 Curing model parameters

Mixtures type	S_{max} (MPa)	S_o (MPa)	b	R^2
LF-CBEM (Control mix)	3925	850	0.0664	0.96
Low OPC-CBEM	8575	2222	0.0860	0.97
High OPC-CBEM	27178	14005	0.4184	0.96
FA-CBEM	10046	1971	0.0833	0.96
GGBS-CBEM	21836	11618	0.1137	0.94

18

From Table 6, the rate of the increase in CBEM stiffness modulus (b) increases as the OPC percentage increases. Also, the rate of increase in stiffness modulus of GGBS-CBEM is slightly higher than those for Low OPC-CBEM and FA-CBEM, which all have the same OPC content (1%), indicating the positive effect of GGBS. Although, it is found that FA replacement has showed better performance than GGBS replacement in improving the long term property of a high strength concrete (Megat Johari *et al.* 2011), using FA produced much lower stiffness as well as a lower rate of increase in comparison to GGBS. This may be attributed to the ability of GGBS mixtures to maintain a higher amount of trapped water relative to FA mixtures replacement (Figure 7). Moreover, GGBS and OPC exhibit very similar chemical oxides, particularly the main oxides CaO and SiO_2. Therefore, this might increase the efficiency of GGBS in by enhancing the hydration process significantly.
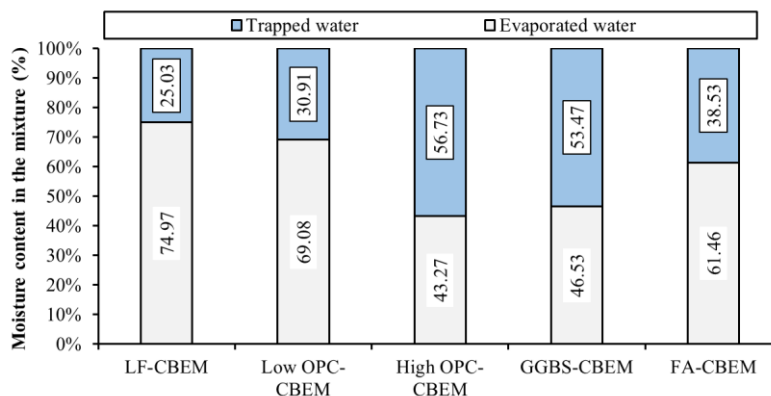

Figure 7 The water content evolution of CBEMs.

4.2. Temperature Influence on Stiffness

Figure 8 presents the CBEM stiffness modulus at 28 days under different testing temperatures, namely 5, 10, 20, 30 and 40°C. Generally, the stiffness modulus decreased with an increase of the temperature; the trend is very clear in both HMA 40/60 and LF-CBEM. However, the

19

variation of stiffness decreased with the presence of active filler, especially GGBS in GGBS-CBEM and High OPC CBEM. This might be considered as an advantage in terms of performance, potentially making the material less prone to cracking at low temperatures and rutting at high temperatures.
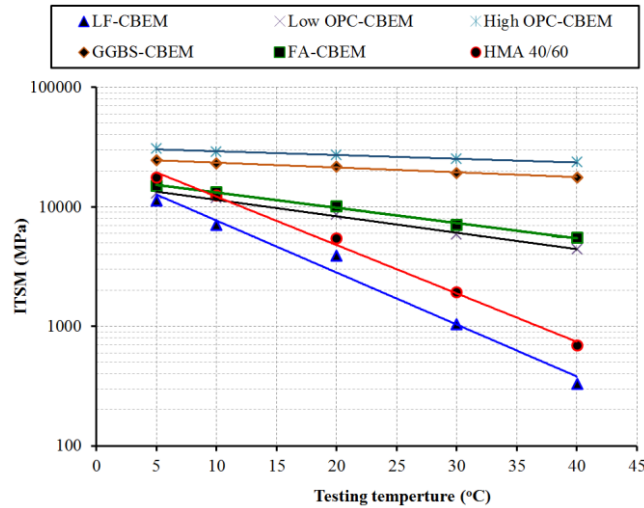

Figure 8 Stiffness modulus of CBEMs at 28 days under different testing temperatures.

An analytical model has been used to describe the temperature sensitivity using the following formula (3) (Bocci *et al.* 2011):

$$log\,S = -\alpha.T + \beta \tag{3}$$

S: is the stiffness modulus at testing temperature T; and α and β: are experimental parameters depending on the material. Temperature sensitivity is expressed by α, the slope of the regression line in a semi-logarithmic plot (Figure 8). Table 7 shows the resulting α, β and R^2 values. The higher the α value, the more temperature sensitive the material.

Table 7 Temperature sensitivity of analytical model results

Mixture type	α	β	R²
LF-CBEM (Control mix)	0.0435	4.3207	0.98
Low OPC-CBEM	0.0138	4.1495	0.99
High OPC-CBEM	0.0031	4.4962	0.98
GGBS-CBEM	0.0040	4.4096	0.98
FA-CBEM	0.0128	4.2474	0.99
HMA 40/60	0.0405	4.4909	0.99

The results are comparable with those published by other authors (Pasetto and Baldo 2010, Bocci *et al.* 2011, Grilli *et al.* 2012, Dondi *et al.* 2014, Pettinari *et al.* 2014).

4.3.Repeated Load Axial Test:

The results of RLAT on the different mixtures are plotted in Figure 9 as the average of three specimens in each mix. The incorporation of OPC and other active fillers resulted in a significant decrease in the permanent strains relative to the control mix (LF- CBEM), implying that CBEMs with OPC, FA and GGBS are much less susceptible to rutting distress. The improvement shown into FA-CBEM relative to low OPC-CBEM is probably rather larger than would be expected based on ITSM data; at this point the reason for this point remains unclear and further investigation is needed.
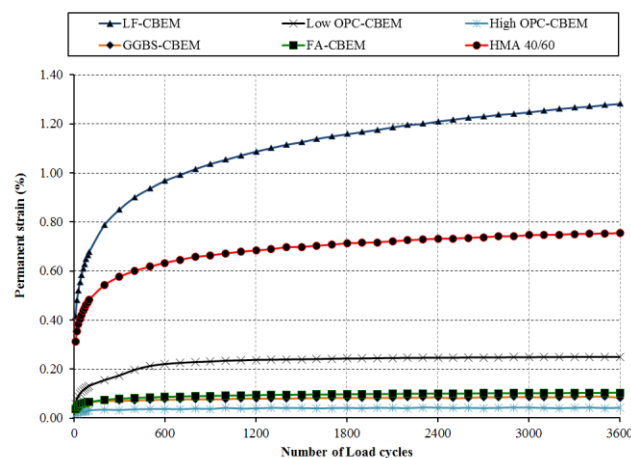
Figure 9 The permanent strain in CBEMs under 100kPa stress.

Normally, the standard RLAT test uses a vertical stress of 100kPa and it is not common to test at higher pressures. However, tests at 200 and 300kPa have been included in the present investigation in order to give a broad picture of what would happen if the CBEMs were used as a surface layer under a high stress level due to direct tyre contact. Under these higher stresses, the sensitivity of result to mixture components became particularly apparent. Figure 10 presents a comparison between the accumulated permanent strains under different stress levels, namely, 100, 200 and 300kPa. Untreated mixtures such as LF-CBEM showed a quite high permanent strain of 3.10% under 200kPa whilst the specimens completely damaged under 300kPa. Also, it was found that incorporating GGBS had a pretty good resistance to permanent deformation particularly under 100kPa relative to High OPC-CBEM.
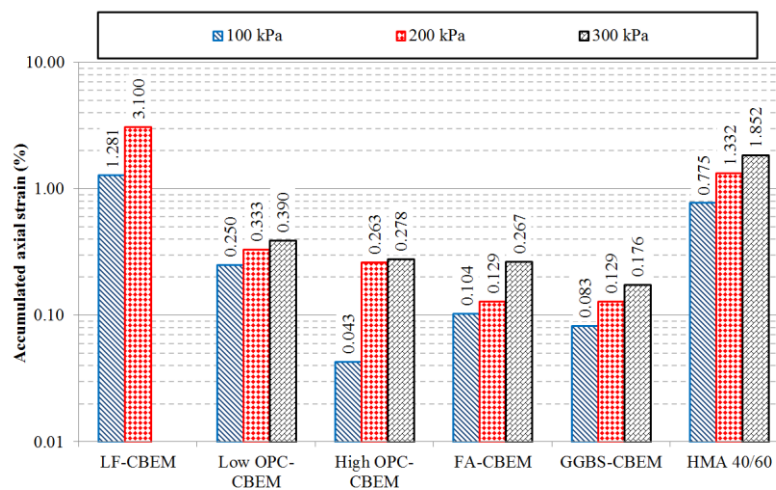

Figure 10 Accumulated permanent strain of CBEMs under different stresses.

In conclusion, the findings generally show that treated CBEMs have an excellent resistance to permanent deformation under high stresses since strain is less than 1% (Thom 2008). Therefore, treated CBEMs can potentially be successfully used in the construction of surface layers for medium to high traffic volume roads.

From Figure 10, it can be found that both filler type and stress level have significant influence on the deformation behaviour of CBEM. A two-way ANOVA statistical analysis was

conducted to determine the impact of stress level and the type of fillers (as introduced for each mix in Table 4) for treated CBEMs. The analysis confirms that both the stress level and the type of fillers are statistically significant at 95% confidence level. ($P_{stress\ level}= 0.010< 0.05$ and $P_{type\ of\ fillers} = 0.012< 0.05$). This is consistent with other works conducted on similar mixes with different types of fillers (Pasetto and Baldo 2012, Al-Hdabi *et al.* 2014, Modarres and Ayar 2014)

4.4. Durability Evaluation:

4.4.1. Moisture Damage

The results in Figure 11 illustrate the potential benefits gained from incorporating OPC and by-product fillers into CBEMs. It is clearly shown that ITSR of treated CBEMs was higher than that for control mix (LF-CBEM) and the equivalent HMA (HMA 40/60). The higher values of ITSR may be related to additional activation of cement hydration, in addition to the high temperature which would accelerate the hydration process of active fillers. The results are consistent with trends noticed in concrete (Lothenbach *et al.* 2008) and lead to the conclusion that CBEMs with FA and GGBS are less susceptible to moisture damage, and this behaviour corresponds to the results obtained for temperature susceptibility (section 4.2).
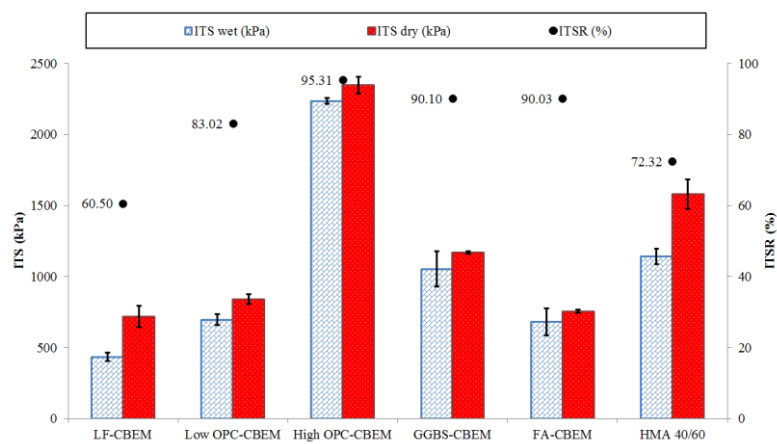

Figure 11 The results of moisture damage for CBEMs.

23

4.4.2. Frost Damage:

Figure 12 plots the ITS values before and after exposure to freeze-thaw cycles. It can be seen that the ITSR values of GGBS-CBEM, FA-CBEM, High OPC-CBEM and HMA 40/60 are approximately in the range from 75% to 80%. However, the other mixtures, LF-CBEM and Low OPC-CBEM, show lower values of around 50 to 60%. Thus, it can be concluded that incorporating waste by-product fillers is very beneficial in making CBEM less susceptible to frost damage and stripping problems. However, a low cement content on its own is not sufficient to withstand the frost damage.
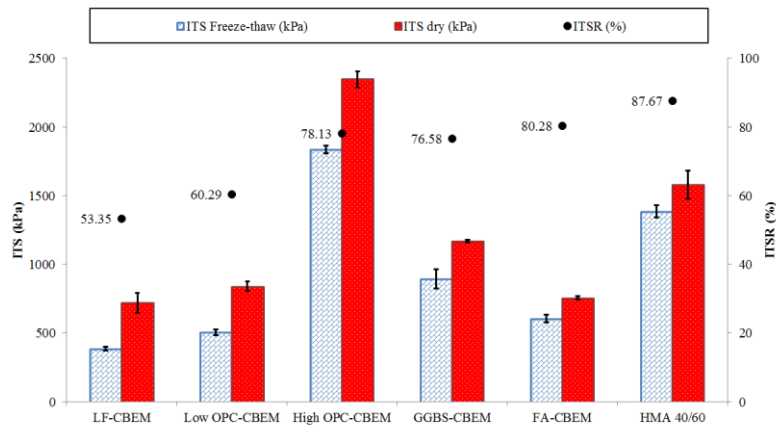

Figure 12 The results of frost damage for CBEMs.

It should be highlighted that there is no universally accepted minimum limit to define CBEMs as durable materials for structural purposes in a pavement. However, the authors would suggest that CBEMs should be considered sufficiently moisture and frost resistant for use in a surface layer if the values of ITSR for both types of damages are more than 70%. Under this criterion, all the CBEMs produced in the present study are durable except LF-CBEM and Low OPC-CBEM.
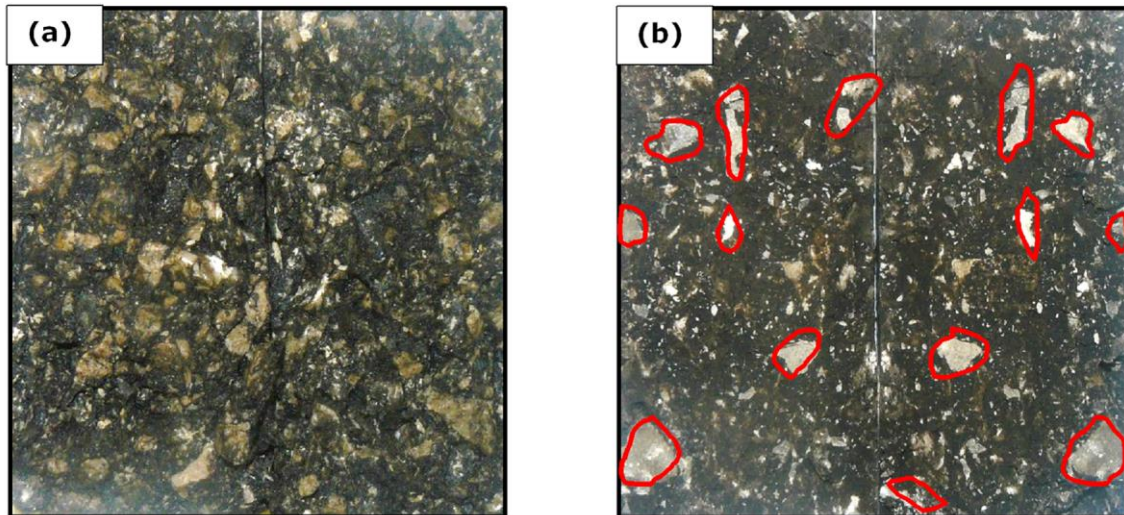
Figure 13 Fracture surface after moisture conditioning (a) without active filler

(LF-CBEM) (b) with active filler (High OPC-CBEM).

Figure 13 (a) and (b) show the fracture surfaces of damaged specimens after ITS testing moisture and frost damages tests for CBEMs. Differences between the CBEMs are found by visual inspection of the fracture surface after testing. The fracture surfaces of LF-CBEM (without active filler) occurred either in the asphalt mastic, or at the interface between the asphalt mastic; no aggregate fractured (Figure 13 (a)). However, for treated CBEM (with active filler) such as High OPC-CBEM, visual observations indicate that a significant portion of the fracture passed through the aggregate particles in the mixture (Figure 13 (b)). This might be related to the improved adhesion between the aggregate and bitumen due to active fillers in treated CBEMs relative to untreated CBEM.

The results also showed that the use of GGBS and FA improved the resistance to both types of damage (moisture and frost) by maintaining approximately the same values as for High OPC CBEM and HMA 40/60. Therefore, it is recommended to use these materials (especially

GGBS) to increase the opportunity to use CBEM as a pavement surface layer. This requires a relatively low OPC value (1%) but produces durable and sustainable CBEMs.

5. Conclusions

The research work aimed at studying the effect of incorporating by-product fillers with low cement content in CBEMs in order to produce a surface course. The investigation was carried out by evaluating both mechanical and durability performances of CBEMs.

The conclusions of the study can be summarized as the following:

- A considerable improvement was achieved in both mechanical properties and durability due to incorporation of low cement content with by-product fillers such as GGBS and FA.

- The replacement of GGBS exhibited better performance than the replacement of FA in CBEMs. This may be seen in the fact that GGBS mixtures maintained a higher amount of trapped water inside the mixture relative to FA replacement which also may be due to similarity of chemical oxides in GGBS relative to OPC. Therefore, this might enhance the hydration process considerably.

- The replacement of GGBS showed a good performance comparable to High OPC-CBEM by means of ITSM, RLAT and resistance to both water and frost damages.

- Treated CBEMs were also found to be less temperature susceptible as the slopes of stiffness modulus variation were less than the equivalent HMA and untreated CBEM (control mix).

- FA and GGBS treated CBEMs showed less susceptibility to severe environmental conditions such as moisture and frost damage. At the same time a tensile strength ratio of more than 70% is recommended to consider the CBEMs as moisture and frost resistant materials.

- Although the new sustainable CBEMs have shown superior performance in terms of stiffness modulus, resistance to permanent deformation and durability properties, fatigue characteristics are needed to be carried out in order to get the full characterisation in structural design of pavement.

6. Acknowledgments

7. References

Al-Busaltan, S., Al Nageim, H., Atherton, W. & Sharples, G., 2012. Mechanical properties of an upgrading cold-mix asphalt using waste materials. *Journal of Materials in Civil Engineering,* 24 (12), 1484-1491.

Al-Hdabi, A., Al Nageim, H., Ruddock, F. & Seton, L., 2014. Laboratory studies to investigate the properties of novel cold-rolled asphalt containing cement and waste bottom ash. *Road Materials and Pavement Design,* 15 (1), 78-89.

Benhelal, E., Zahedi, G., Shamsaei, E. & Bahadori, A., 2013. Global strategies and potentials to curb co2 emissions in cement industry. *Journal of Cleaner Production,* 51 (0), 142-161.

Bocci, M., Grilli, A., Cardone, F. & Graziani, A., 2011. A study on the mechanical behaviour of cement–bitumen treated materials. *Construction and Building Materials,* 25 (2), 773-778.

Dondi, G., Tataranni, P., Pettinari, M., Sangiorgi, C., Simone, A. & Vignali, V., 2014. Crumb rubber in cold recycled bituminous mixes: Comparison between traditional crumb rubber and cryogenic crumb rubber. *Construction and Building Materials,* 68, 370-375.

Eckmann, B., Delfosse, F. & Conan, J., 2004. Cold bituminous mixtures for surface courses. *Proceedings of the 3rd Eurasphalt and Eurobitume Congress.* Vienna.

Ellis, C., Zhao, B., Barnes, J. & Jones, N., 2004. Properties of ggbs-bitumen emulsion systems with recycled aggregates. *Road materials and pavement design,* 5 (3), 373-383.

European Committee for Standarization, 2005. Bs en 12697-25 bituminous mixtures. Test methods for hot mix asphalt. *Part 25: Cyclic compression test.* London, UK: British Standards Institution.

European Committee for Standarization, 2006. Bs en 13108-1 bituminous mixtures- material specifications. *Part 1: Asphalt Concrete* London, UK: British Standards Institution.

European Committee for Standarization, 2012. Bs en 12697-26: Bituminous mixtures: Test methods for hot mix asphalt. *Part 26: Stiffness.* London, UK: British Standards Institution.

Fang, X., Garcia, A., Winnefeld, F., Partl, M.N. & Lura, P., 2014. Impact of rapid-hardening cements on mechanical properties of cement bitumen emulsion asphalt. *Materials and Structures*, 1-12.

García, A., Lura, P., Partl, M.N. & Jerjen, I., 2013. Influence of cement content and environmental humidity on asphalt emulsion and cement composites performance. *Materials and Structures,* 46 (8), 1275-1289.

Gómez-Meijide, B. & Pérez, I., 2014. Effects of the use of construction and demolition waste aggregates in cold asphalt mixtures. *Construction and Building Materials,* 51 (0), 267-277.

Grilli, A., Graziani, A. & Bocci, M., 2012. Compactability and thermal sensitivity of cement–bitumen-treated materials. *Road Materials and Pavement Design,* 13 (4), 599-617.

Head, R.W., 1974. An informal report of cold mix research using emulsified asphalt as a binder. *Association of Asphalt Paving Technologists* 43, 110-131.

Humphreys, K. & Mahasenan, M., 2002. *Toward a sustainable cement industry. Substudy 8: Climate change (geneva: World business council for sustainable development)* [online]. http://www.wbcsdcement.org/ [Accessed Access Date 01/06/2015].

Khalid, H.A. & Monney, O.K., 2009. Moisture damage potential of cold asphalt. *International Journal of Pavement Engineering,* 10 (5), 311-318.

Li, G., Zhao, Y., Pang, S.-S. & Huang, W., 1998. Experimental study of cement-asphalt emulsion composite. *Cement and Concrete Research,* 28 (5), 635-641.

Liebenberg, J. & Visser, A., 2004. Towards a mechanistic structural design procedure for emulsion-treated base layers: Technical paper. *Journal of the South African Institution of Civil Engineering,* 46 (3), p. 2-9.

Lothenbach, B., Matschei, T., Möschner, G. & Glasser, F.P., 2008. Thermodynamic modelling of the effect of temperature on the hydration and porosity of portland cement. *Cement and Concrete Research,* 38 (1), 1-18.

Lu, C.-T., Kuo, M.-F. & Shen, D.-H., 2009. Composition and reaction mechanism of cement–asphalt mastic. *Construction and Building Materials,* 23 (7), 2580-2585.

Megat Johari, M.A., Brooks, J.J., Kabir, S. & Rivard, P., 2011. Influence of supplementary cementitious materials on engineering properties of high strength concrete. *Construction and Building Materials,* 25 (5), 2639-2648.

Miljković, M. & Radenberg, M., 2014. Fracture behaviour of bitumen emulsion mortar mixtures. *Construction and Building Materials,* 62, 126-134.

Miljković, M. & Radenberg, M., 2016. Effect of compaction energy on physical and mechanical performance of bitumen emulsion mortar. *Materials and Structures,* 49 (1-2), 193-205.

Modarres, A. & Ayar, P., 2014. Comparing the mechanical properties of cold recycled mixture containing coal waste additive and ordinary portland cement. *International Journal of Pavement Engineering,* (ahead-of-print), 1-14.

Modarres, A. & Ayar, P., 2016. Comparing the mechanical properties of cold recycled mixture containing coal waste additive and ordinary portland cement. *International Journal of Pavement Engineering,* 17 (3), 211-224.

Mohammed, M.K., Dawson, A.R. & Thom, N.H., 2013. Production, microstructure and hydration of sustainable self-compacting concrete with different types of filler. *Construction and Building Materials,* 49, 84-92.

Nassar, A.I., Thom, N. & Parry, T., 2016. Optimizing the mix design of cold bitumen emulsion mixtures using response surface methodology. *Construction and Building Materials,* 104, 216-229 Available from: http://www.sciencedirect.com/science/article/pii/S0950061815307376.

Needham, D., 1996. *Developments in bitumen emulsion mixtures for roads*. PhD thesis. University of Nottingham.

Niazi, Y. & Jalili, M., 2009. Effect of portland cement and lime additives on properties of cold in-place recycled mixtures with asphalt emulsion. *Construction and Building Materials,* 23 (3), 1338-1343.

Nikolaides, A., Year. A new design method for dense cold mixturesed.^eds. *The First European Symposium on Performance and Durability of Bituminous Materials*, University of Leeds, UK, 259.

Ojum, C., Kuna, K., Thom, N.H. & Airey, G., Year. An investigation into the effects of accelerated curing on cold recycled bituminous mixesed.^eds. *International Conference on Asphalt Pavements, ISAP* Raleigh, North Carolina, USA, 1177-1188.

Oke, O.L., 2011. *A study on the development of guidelines for the production of bitumen emulsion stabilised raps for roads in the tropics*. PhD thesis. University of Nottingham.

Oner, A. & Akyuz, S., 2007. An experimental study on optimum usage of ggbs for the compressive strength of concrete. *Cement and Concrete Composites,* 29 (6), 505-514.

Oruc, S., Celik, F. & Akpinar, M.V., 2007. Effect of cement on emulsified asphalt mixtures. *Journal of Materials Engineering and Performance,* 16 (5), 578-583.

Pasetto, M. & Baldo, N., 2010. Experimental evaluation of high performance base course and road base asphalt concrete with electric arc furnace steel slags. *Journal of Hazardous Materials,* 181 (1), 938-948.

Pasetto, M. & Baldo, N., 2012. Laboratory investigation on foamed bitumen bound mixtures made with steel slag, foundry sand, bottom ash and reclaimed asphalt pavement. *Road Materials and Pavement Design,* 13 (4), 691-712.

Pettinari, M., Dondi, G., Sangiorgi, C. & Hededal, O., 2014. The effect of cryogenic crumb rubber in cold recycled mixes for road pavements. *Construction and Building Materials,* 63, 249-256.

Schmidt, R., Santucci, L. & Coyne, L., 1973. Performance characteristics of cement-modified asphalt emulsion mixes. *Association of Asphalt Paving Technologists* 42, 300-319.

Serfass, J.-P., Poirier, J.-E., Henrat, J.-P. & Carbonneau, X., 2004. Influence of curing on cold mix mechanical performance. *Materials and Structures,* 37 (5), 365-368.

Terrell, R. & Wang, C., 1971. Early curing behavior of cement modified asphalt emulsion mixtures. *Association of Asphalt Paving Technologists* 40, 108-125.

Thanaya, I.N.A., 2003. *Improving the performance of cold bituminous emulsion mixtures (cbems): Incorporating waste*. PhD thesis. University of Leeds.

Thanaya, I.N.A., Zoorob, S. & Forth, J., 2009. A laboratory study on cold-mix, cold-lay emulsion mixtures. *Proceedings of the ICE-Transport,* 162 (1), 47-55.

Thom, N., 2008. *Principles of pavement engineering* London, UK: Thomas Telford Publishing Ltd.

Wang, F., Liu, Y. & Hu, S., 2013. Effect of early cement hydration on the chemical stability of asphalt emulsion. *Construction and Building Materials,* 42, 146-151.

Wang, Z. & Sha, A., 2010. Micro hardness of interface between cement asphalt emulsion mastics and aggregates. *Materials and structures,* 43 (4), 453-461.