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Improving Asphalt Emulsion Mixtures Properties Containing Cementitious Filler by Adding GGBS

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ABSTRACT

Production and use of sustainable Cold Asphalt Emulsion Mixtures (CAEM), that comparable with traditional hot mixtures, relevant for roads and highways constructions might achieve several benefits such as reduce energy consumption, CO_{2e} emissions, and total expenses. Furthermore, some of by product and waste materials could be incorporated in these mixtures to enhance their properties.

The purpose of this investigation is to produce CAEM incorporated by producing material/s with mechanical properties and water sensitivity comparable with conventional hot asphalt mixtures. The mechanical properties have been evaluated by conducting Indirect Tensile Stiffness Modulus (ITSM) and Uniaxial Compressive Cyclic Test (UCCT), while water sensitivity was evaluated by determining the Indirect Tensile Strength Ratio (ITSR). A Waste Fly Ash (WFA) has been incorporated instead of mineral filler with different percentages (0−6% by weight of aggregate), while Ground Granulated Blast Furnace Slag (GGBS) was added with dosages ranging from 0−3% by total mass of aggregate to produce the novel CAEMs.

The results have revealed a considerable enhancement in the performance of the new CAEM mixtures as a result of using WFA and GGBS in comparison with the conventional hot asphalt mixture properties.

KEYWORDS: Cold asphalt emulsion mixtures; Hot asphalt; Waste materials; by product materials; GGBS

INTRODUCTION

Cold Asphalt Emulsion Mixtures (CAEMs) are defined as bituminous mixtures prepared at ambient temperature utilising bitumen emulsion instead of bitumen. Many advantages can be achieved when utilising cold mixtures instead of conventional hot mixtures in terms of cost effectiveness and environmental aspects. However, reduced early mechanical properties, high water sensitivity, and highly sensitive to rainfall at early stages of installation are the main disadvantages of these mixtures (Needham, 1996, Read and Whiteoak, 2003, Oruc et al., 2007, Thanaya et al., 2009). In UK, uses of CAEMs as structural layer are very limited because of its inferior mechanical properties, especially at early life, and their use is largely restricted to surface treatment, such as surface dressing, slurry surfacing, and reinstatement work on low trafficked highways and walkways (Highway Authority and Utility Committee (HAUC), 1992), (Read and Whiteoak, 2003). Chevron Research Company has conducted several researches to evaluate the performance of CAEMs. These researches stated that CAEMs need 2−24 months at site to achieve the optimum strength, dependent on the conditions of weather. Inappropriately, several regions around the world, such as UK, are not assisting to minimize the curing period, cold, rainy, and humid through the year (Needham, 1996).

The primary design procedures used Marshall hammer or the California kneading compactor. As nowadays many laboratories around the world use Superpave gyratory compactor also to prepare Hot Mix Asphalt (HMA), several studies such as Wayne et al. (1999) and James (2002) suggested this procedure to prepare CAEMs. In CAEM design method, the compactor was utilised both to make samples for mechanical properties, durability testing, and to prepare samples for optimal fluids determination for compaction. They recommended that it can be used instead of California Kneading compactor to prepare CAEMs.

Literature background

There are several studies that were conducted to enhance CAEMs' properties. A preliminary study undertaked by Head (1974) stated the results of research study on cement treated CAEMs. He revealed that addition of a little amount of cement (1%) improved the stability about three times in comparison with untreated mixtures. Also, the samples without cement were disintegrated after 1 day immersion in water, whereas there was no deterioration inspected for cement treated samples. Li et al. (1998) assessed the mechanical properties of a cement asphalt

emulsion mixture, which is nominated as CAEC. They reported that these mixtures gained several properties of both asphalt and cement, such as the lower temperature sensitivity and longer fatigue life of cement concrete, the greater flexibility, and toughness of asphalt concrete. To sum up the previous studies, ordinary Portland cement and rapid setting cement enhanced the performance of CBEMs, but they have several challenges that are related to environmental impact and cost effectiveness.

As Portland cement is expensive, therefore this study will focus on incorporating of by product materials as a replacement to mineral filler to improve the performance of cold asphalt emulsion mixtures.

There were some attempts to reuse by-product and waste materials to enhance CAEMs such as pulverised fly ash, steel slag and crushed glass (Thanaya, 2003, Thanaya et al., 2006). Several advantages might be achieved when adopting CAEMs containing by product materials as mineral filer such as, but not limited to, enhance the mechanical properties and durability; economic benefits and ecological gains.

Thanaya et al. (2006) implemented an experimental work to investigate the suitability of incorporating Pulverised Fly Ash (PFA) instead of mineral filler in CAEM. They stated that the produced mixtures had a comparable stiffness modulus with traditional hot mixtures at full curing circumstances. Another study undertaken by Shakir et al. (2012) produced a CAEM, using close graded aggregate, with mechanical properties that are similar to conventional hot mixtures. Their attainment was because of incorporating of a waste fly ash instead of filler, nominated as LJMU-FA1, which has a cementitious action.

Aim of the study

The main theme of this investigation is to produce a new CAEM with a gap graded material, nominated as Cold Rolled Asphalt (CRA) within this research, with mechanical properties, and water sensitivity comparable or better than conventional hot rolled asphalt utilising by product constituents. A Waste Fly Ash (WFA) was used instead of conventional mineral filler, and GGBS was added in the range from 0−3% by total mass of aggregate. The mechanical properties enhancements were evaluated using the Indirect Tensile Stiffness Modulus (ITSM)

and the Uniaxial Compressive Cyclic Test (UCCT), while water sensitivity was assessed by the Indirect Tensile Strength Ratio (ITSR) determination.

RESEARCH METHODOLOGY

Materials and Sample Preparation

Materials

The coarse aggregate and fine aggregate were crushed granite, and the physical properties of these substances are presented in Table 1. While, limestone dust and WFA, which is a fly ash generated from burning a waste sludge to produce energy, were incorporated as mineral filler. The chemical concentrations of the said fillers are shown in Table 2.

Annually, 1 million tonnes of the waste sludge are generated in European countries. As shown in Table 2, the main ingredients of WFA are SiO_2, CaO, and Al_2O_3. Therefore, a hydration process might be happened when mixed with CRA constituents. Also, WFA has a high ability to absorb water, and it might absorb the trapped water incorporated in CAEMs. One type of by-product material (GGBS) was added as an admixture to enhance the performance of CRA containing WFA. Blast furnace slag is a by-product from the iron making industry. GGBS is obtained by grinding the quenched molten iron slag. About 2.2 million tonnes of GGBS are produced annually in the UK.

Previous studies have used dense gradation to produce CBEMs (Needham, 1996, Thanaya et al., 2009, Shakir et al., 2012). However, gap-graded has been recommended in this work to produce CRA mixtures, because of using this gradation successfully to produce HMA, suitable for heavy traffic surface course. The gradation of both CAEM and HMA mixtures was as per BS EN 13108-4 for 55/14C gap-graded surface course mixture (British Standard Institution, 2006). Table 3 demonstrates the selected aggregate gradation. According to BS EN 933-1 (British Standard Institution, 1997), aggregate constituents were dried and separated to the required sizes.

K3-60 bitumen emulsion was incorporated to create CRAs. While two types of bitumen i.e. 50-pen and 125-pen were added to create HMAs. The properties of K3-60 are shown in Table 4, while Table 5 presents the properties of 50-pen and 125-pen bitumen.

Preparation of samples

All CAEMs were designed and prepared in accordance to MS-14 standard which is recommended by (Asphalt Institute, 1989). According to the selected materials characteristics, pre-wetting water content, optimum total liquid content at compaction, and optimum residual bitumen content for the control mixtures were 5%, 15.16%, and 7%, respectively. Different amounts of WFA have been incorporated as a replacement to limestone dust i.e. 0, 1.5, 3, 4.5, and 6% by the whole weight of aggregate. On the other hand, four percentages of GGBS were selected which were 0, 1, 2, and 3% by the whole weight of aggregate. Generally, the mixing and compacting temperatures for CAEM samples were at ambient temperature i.e. 20°C.

In contrast, as per BS 594987 Annex H, 5.5% bitumen content has been incorporated to the total weight of aggregate to produce HMA (British Standard Institution, 2010). The mixing temperatures for 50-pen and 125-pen HMAs were (165–175°C) and (150–160°C), respectively.

Testing Methods

In this research, the mechanical properties of cold and hot mixtures have been investigated by conducting ITSM and UCCT tests while water susceptibility of the whole mixtures was assessed by determining the Indirect Tensile Strength Ratio (ITSR).

ITSM test

Stiffness modulus has been measured by applying indirect tension to a cylindrical specimen as per BS EN 12697-26, and the resultant modulus was named as Indirect Tensile Stiffness Modulus (ITSM) (British Standard Institution, 2012). The test was implemented at 20°C using HYD 25 universal testing apparatus shown in Figure 1. In this method, the selected details of applied load parameters were: the rise-time, which is the time taken for the applied load to increase from zero to the maximum value, was (124 ± 4) micro strain; transient peak horizontal deformation was (5±2) µm; number of conditioning load pulses was 5; and number of test pulses was 5.

Each CAEM sample was cured with: i) the sample was left in the mould at 20°C for one day, ii) extruded the sample from the mould then cured in a ventilated oven for another day at 40°C, then iii) the sample was left at 20°C which represents lab temperature until be tested at the designated ages. The ITSM was tested at 20°C at 2, 7, 14, and 28 days. It is worthy to state that

this procedure of curing can be achieved after 7–14 days in the site as reported by (Jerkins, 2000).

UCCT test

The influence of incorporating of GGBS to CAEM mixtures, which is containing WFA on creep performance, was investigated by conducting UCCT at 40°C. The test has been implemented as per BS EN 12697-25 (British Standard Institution, 2005), also HYD 25 universal testing apparatus has been utilised. Figure 2 shows the creep test configuration. In this test, the diameter of the loading platen is taken smaller than that of the sample to ensure a certain confinement under the applied cyclic axial stress. Throughout the test, the variation in height of the sample is recorded at a certain number of pulses. Accordingly, the relationship between the accumulative axial strains (ε) of the test sample with number of load applications (pulses) can be drawn to produce a creep curve. A preload of 20 KPa was applied for 2 mins, then a typical value of (100 ± 2) KPa was used for the repeated load.

For this test, each sample was left in the mould for one day at 20°C (lab temperature), then after being extruded cured at 40°C in an oven for 14 days. This curing system is to ensure that all trapped water will be evaporated to achieve the full curing situation.

Water sensitivity test

Water sensitivity was evaluated by determining the ITSR. As per BS EN 12697-12, two sets of specimens have been prepared i.e. dry and wet specimens (British Standard Institution, 2008). Each dry sample was cured with: 1 day at 20°C (as it left in the mould), cured in an oven for 1 day at 40°C, and lastly placed in a flat shelf for 3 days at lab temperature (20°C). After this curing process, the whole dry samples were tested at 25°C by ITS test. On the other hand, each wet sample was cured at 20°C (left in mould) for 1 day, another day at 40°C (left in an oven), then it was subjected for 30 mins to 6.7 KPa vacuum pressure and submerged in water for other 30 mins. Lastly it was immersed for 3 days at 40°C (in a water bath). After completing the curing process and same as in dry case samples, ITS test was conducted at 25°C to determine the ITSR which represents the ratio of ITS results for wet to dry samples.

RESULTS AND DISCUSSION

ITSM Results

All CAEM samples were tested at ages of 2, 7, 14 and 28 days in order to identify the effect of replacement of conventional mineral filler with WFA and GGBS addition on the ITSM results.

The results of these tests are shown in Figures 3-5. Numerous points can be reported from ITSM test results. The stiffness modulus of CAEMs increased extensively with the increased ratio of WFA replacement for a conventional mineral filler. This improvement is due to the cementitous reaction generated from using WFA and the ability of this material to absorb the trapped water in CAEM mixtures. Furthermore, ITSM results for CAEMs improved when the curing time increased, specifically with higher ratios of WFA. However, there was no an obvious change in ITSM results for HMA mixtures with time.

Furthermore, when 1% of GGBS was added to CAEM with 3% WFA, the stiffness modulus after 2 days improved almost twice. It is worthy to state that this value is greater than those of 125-pen HMAs, Figure 4. Moreover, the addition of 2% GGBS to CAEMs with 6% WFA improved the ITSM for about 40% after 2 days, and this value is greater than the target value of the 50-pen HMA, Figure 5. Finally, the target stiffness for 50-pen HMA can be obtained after four days curing of the CAEM mixtures containing 1% GGBS and 6% WFA.

On the other hand, three sets of samples have been cured at lab temperature i.e. 20 °C for 28 days and then tested at 5°C, 20°C, and 40°C i.e. low, moderate, and high temperatures, respectively, to investigate the performance of the produced mixtures at different climates temperatures, Figure 6. Several points can be reported from Figure 6 which are: i) there was no possibility to conduct the test for untreated CAEM at 40°C; ii) ITSM at 40°C for mixtures with 3%WFA+1%GGBS is higher than those for HMAs; iii) ITSM at 5°C cold mixtures with 3%WFA+1%GGBS is lower than those for HMAs and cold mixtures with 6%WFA (without GGBS), therefore it can be stated that these cold mixtures might be more suitable in cold regions; and iv) CAEM with 3%WFA+1%GGBS presented a considerable lower temperature susceptibility than conventional HMAs.

UCCT Results

Figure 7 shows the effect of replacement of limestone dust with WFA on creep stiffness of CAEM mixtures, while Figure 8 shows the effect of addition of 1% of GGBS to the CAEMs containing 3% of WFA on creep stiffness. These Figures demonstrate the encouraging effect of WFA and GGBS on the creep properties of the new CAEM mixtures. Creep stiffness increased for about five times more than those for 50-pen HMA with replacement of 3% of WFA instead of conventional mineral filler in CAEM. Also, when 1% of GGBS was added to the CAEM with 3% WFA, the creep stiffness increased for about ten times of those for 50-pen HMA.

Water sensitivity results

ITSR as per BS EN 12697-12 was adopted to investigate the effect of replacing mineral filler with WFA as well as addition of GGBS to CAEMs.

As presented in Figure 9, ITSR improved extensively with WFA ratio increment. It is obviously revealed that ITSR for CAEM with 4.5 and 6% WFA have been about twice those for untreated mixtures. Moreover, it can be reported that these values comply with the standards for asphalt concrete and are similar to those for HMA. This behaviour of the CRA with WFA can be attributed to the hydration process between WFA and the existing water. Also, the conditioning of cold asphalt sample at 40°C (relatively high temperature) motivates this process.

In turn, there is a further outstanding from addition GGBS to the CRAs with WFA, particularly with higher amounts of WFA. It can be seen from Figure 9 that ITSR values increased considerably when GGBS has been added, especially with high ratios of WFA. It is interesting to see that with the addition of GGBS, the ITS results started to be higher than those for the conventional HMA. More remarkably, the ITSR is more than 100%, which can be attributed to the positive influence of water conditioning at a high temperature for cold mixtures.

The hydration process and the generation of a minor binder from the hydration of the WFA in the presence of GGBS are the main reasons for this substantial improvement. Additionally, the said hydration process accelerated under a relatively high temperature.

MICROSTRUCTURE OBSERVATION BY SCAN ELECTRON MICROSCOPY

In this research, the morphology and microstructure of the limestone dust and the modified filler i.e. 3% WFA+1% GGBS has been studied by means of Scan Electron Microscopy (SEM). The main idea of this is to take as clear photograph as possible from the powder and the paste produced due to the hydration process between these materials and the water incorporated in CAEMs. The two filler materials were mixed with water to produce the required mastics. In accordance with the standard procedure to conduct SEM analysis, small pieces of mastics after 7 and 28 days curing time were taken and coated with gold to undertake SEM observation. SEM test was conducted with a high vacuum and 5-10 kV test voltage.

Figure 10 shows the SEM test images for the control filler powder, modified filler (3%WFA+1%GGBS), and the mastics produced from these filler after 7 and 28 days curing times. It is clearly shown that the modified filler has a dense structure, and its density increased significantly with time. This structure can be attributed to the hydration process between the modified filler and the trapped water to generate Calcium Silicate Hydrate (CSH) gel which is extensively distributed and increased with curing time increase. While the morphology of the control mastic which is generated from mixing limestone dust filler with water did not show any remarkable change in the microstructure during the curing times i.e. 7 and 28 days.

Accordingly, the little evolution in the stiffness modulus of the control CBEM can be attributed to the evaporation of the trapped water. While the significant improvement in stiffness modulus results for CBEMs containing cementitious fillers i.e. 3%WFA+1%GGBS can be attributed to generate a new binding material due to the hydration process of the cementitious filler and the trapped water.

CONCLUSION

Most of the previous improvements to the mechanical properties and durability of CBEM's were achieved by utilising cost minus materials and having significant carbon footprint materials, such as Portland cement, lime, and rapid setting cement. Consequently, this study has concentrated on producing innovative gap-graded CAEMs incorporated by-product materials to address a new cost effective and environmental friendly alternative. A waste material named as WFA was used instead of conventional mineral filler, while GGBS (by-

product material) was used successfully as an additive to activate the strength of the new CAEM mixtures. The followings can be concluded according to the experimental results of this investigation:

1. By means of ITSM results, the stiffness modulus of CAEM containing WFA increased significantly, especially with higher amounts of filler replacement i.e. 4.5% and 6%. Also, there is a further outstanding improvement when GGBS was added to CAEMs containing WFA as filler. The addition of 1% of GGBS to CRAs containing 3% WFA increased the stiffness modulus after two days for more than twice (compared with CAEM with 3% WFA), and this value is already more than the target value for 125-pen HMA.
2. The UCCT results revealed that there is a substantial development in the permanent deformation resistance for the CAEM mixtures containing WFA with and without GGBS addition.
3. In accordance to water sensitivity results, the durability of CAEM containing 4.5% or 6% WFA is about twice that of the control CAEM, and these values achieve the standards for asphalt concrete and are similar to those for HMA. Moreover, there is a further outstanding gained from the addition of GGBS to the CAEM containing WFA, especially at higher percentages of WFA. More remarkably, the ITSR are more than 100%, which can be attributed to the positive influence of water conditioning at high temperature for cold mixtures.
4. Based on the mechanical properties and durability test results, it can be recommended that the optimal WFA and GGBS to be used in the industry is 3% and 1%, respectively. These fast curing mixtures can achieve the required stiffness modulus (2000 MPa) after two days. Therefore, it can be introduced as a suitable replacement to the conventional HMA.

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Table 1. Physical properties of aggregates

Material	Property	Value
Coarse aggregate	Bulk specific gravity	2.79
	Apparent specific gravity	2.83
	Water absorption, %	0.60
Fine aggregate	Bulk specific gravity	2.68
	Apparent specific gravity	2.72
	Water absorption, %	1.60
Mineral filler	Specific gravity	2.71

Table 2. Chemical compositions of limestone dust, WFA and GGBS

Element	Concentration, %		
	Limestone dust	WFA	GGBS
CaO	49.71	62.21	40.37
MgO	2.580	3.110	3.650
SiO_2	4.700	27.25	37.47
Al_2O_3	0.300	2.870	4.760
Fe_2O_3	1.840	0.150	0.150
K_2O	0.100	0.350	0.620
Na_2O	0.030	1.780	2.550

Table 3. Aggregate gradation for 55/14C gap graded surface course (European Committee for Standardization, 2006)

sieve size, mm	% passing (specification range)	% by mass (passing mid)
20	100	100
14	98-100	99
10	42-63	52
2	40	40
0.5	19-31	25
0.25	9-31	20
0.063	6	6

Table 4. Bitumen emulsion properties

Bitumen emulsion (K3-60)	
Property	Value
Appearance	Black to dark brown liquid
Boiling point, ºC	100ºC
Relative density at 15ºC, Mg/m3	1.05
Residue by distillation, %	64

Table 5. Bituminous binders' properties

	Bituminous binder type	
Property	(40−60)	(100−150)
Appearance	Black	Black
Penetration at 25ºC	43	122
Softening point, ºC	54	43.6
Density at 25ºC, Mg/m^3	1.02	1.05