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A Novel Cold Asphalt Concrete Mixture for Heavily Trafficked Binder Course

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Abstract**—**This study aims at developing a novel cold asphalt concrete binder course mixture by using Ordinary Portland Cement (OPC) as a replacement for conventional mineral filler (0%-100%) with new by-product material (LJMU-A2) used as a supplementary cementitious material. With this purpose, cold asphalt concrete binder course mixtures with cationic emulsions were studied by means of stiffness modulus whereas water sensitivity was assessed by measuring the stiffness modulus ratio before and after sample conditioning.

The results indicate that a substantial enhancement in the stiffness modulus and a considerable improvement of water sensitivity resistance is achieved by adding LJMU-A2 to the cold asphalt mixtures as a supplementary cementitious material. Moreover, the addition of LJMU-A2 to those mixtures leads to a stiffness modulus after 2-day curing compared to that obtained with Portland cement, which occurs after 7-day curing.

Keywords**—**Binder course, cold mix asphalt, cement, stiffness modulus, water sensitivity.

I. Introduction

COLD BITUMINOUS ASPHALT MIXTURES (CBEMs) provide a sustainable, cost-effective and energy efficiency alternative to traditional hot mixtures because no heating is required to manufacture CBEMs. However, these mixtures have a comparatively low initial strength and CBEM is considered to be an evolutionary material, mainly in its early life where the initial cohesion is low and builds up slowly [1]. On the other hand, asphalt concrete is by far the most common mixture in use as a binder course and base in road pavements in the UK. Having a continuous grade offering a good aggregate interlock results in this material having very good load-spreading properties as well as a high resistance to permanent deformation [2], [3].

Cold mix asphalt mixtures are defined as bituminous materials mixed using cold aggregates and binder [4]. Accordingly, both economic and environmental advantages can be achieved when compared with traditional hot mix asphalt by eliminating the need to heat the large volumes of aggregate [5], [6]. Nevertheless, those mixtures are inferior with regard to mechanical properties, high air voids, rain sensitivity and the long curing time needed to achieve their final strength [7], [8].

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Cement utilisation in asphalt mixture is not a new idea; Portland cement was firstly used as a filler in warm-mixed bituminous mixtures to prevent stripping of the binder from previously dried aggregate [9].

Cement is extensively used in cold mix asphalt and its role has been investigated in several studies. OPC can considerably develop the early stiffness, decrease the permanent deformation and increase the durability of the mixtures.

An initial study conducted by [10] demonstrated that the addition of cement to the emulsion-treated mixes resulted in acceleration of the rate of development of the resilient modulus. Head [11] indicated that, with 1% OPC addition, Marshall Stability of modified cold asphalt mix increased by around three times compared with un-treated mix. Also, [12] showed that when cement was added to the aggregate at the time the asphalt emulsion was combined, the mixes cured faster, and more resilient modulus (Mr) developed rapidly. Another study, implemented by [8], concluded that OPC addition has enhanced the mechanical properties, namely: stiffness modulus, permanent deformation resistance and fatigue strength of the emulsified mixes. An experimental study by [13] assessed the hydration process, the microstructure and the mechanical properties of mortar prepared with a new mixed binder made of a cement slurry and a small quantity of asphalt emulsion (SS-1 and CSS-1). Oruc et al. [14] conducted experiments to assess the mechanical properties of emulsified asphalt mixtures including 0-6% OPC which was substituted for mineral filler. Significant improvement was revealed with high percentage of OPC addition and they reported that cement-modified asphalt emulsion mixtures might be used as a structural layer. Thanaya et al. [15] implemented experiments adding 1-2% rapid-setting cement to the cold mix asphalt and they showed that strength development increased and improvements occurred in the mechanical properties of the modified cold mixes, especially in the early days.

Al-Hdabi et al. [16] conducted experiments on the mechanical properties and water sensitivity of cold-rolled asphalt (CRA) by using cement as a replacement for the traditional filler and waste bottom ash (WBA). The results showed a substantial improvement in the mechanical properties in terms of stiffness modulus and uniaxial creep tests as well as the water sensitivity. Thus, new cold-rolled asphalt was created.

Fang et al. [17] mentioned three reasons for the hardness of Cement Asphalt Emulsion Composites (CAEC), namely: breaking of the emulsion, water evaporation and cement hydration. They also demonstrated two possible benefits of

CAEC, which are the lower temperature susceptibility compared with asphalt concrete and the flexibility, which is higher than that of cement concrete.

On the other hand, the re-use of waste and by-product materials which have pozzolanic activity in cold asphalt mixtures is usually encouraged for two reasons: environmental sustainability and economic advantages. Consequently, LJMU-A2 has the probability of working as a supplementary cementing material (SCM) which can be substituted for OPC. This offers a positive effect in sustainability by reducing the cement content of cold asphalt mixtures.

From the aforementioned studies, the benefits of using OPC in cold asphalt mixtures can be concluded. In this research, partial replacement of OPC by pozzolans from industrial waste has been carried out to improve the performance of cold asphalt concrete binder course mixtures by formation of cementitious hydrated products through activating pozzolanic materials. The indirect tensile stiffness modulus test (ITSM) was used to assess the effects of using OPC together with supplementary cementing material on the mechanical properties of cold mix asphalt, whereas water sensitivity was examined by assessing the stiffness modulus ratio (SMR) before and after sample conditioning.

II. Materials

A. Materials

The materials utilised in this study are granite aggregate, emulsified asphalt, Portland cement, limestone dust, LJMU-A2 and water.

A dense aggregate gradation for asphalt concrete binder course AC-20 was used in this research in accordance with EN 13108-1 [18], as shown in Table I. It is generally used on the asphalt pavement binder course in the UK. The physical specifications of the crushed coarse and fine aggregate are listed in Table II.

TABLE I
AGGREGATE GRADING FOR ASPHALT CONCRETE 20 MM DENSE BINDER COURSE MIXTURES

Test sieve aperture size, mm	% by mass passing specification range	% by mass (passing mid)
20	99-100	100
10	61-63	62
6.3	47	47
2	27-33	30
0.250	11-15	13
0.063	6	6

Cationic slow-setting bitumen emulsion (C 60 B5) was used in all the mixtures. Table III shows the properties of the chosen bitumen emulsion. Furthermore, two grades of bitumen, soft bitumen of penetration grade (100/150) and hard bitumen of penetration grade (40/60), have been used to make hot binder course mixtures. Table IV shows the characteristics of these binders.

Traditional mineral filler (limestone dust) and a commercially available Ordinary Portland Cement type CEM-II/A/LL 42.5-N have been used throughout the research as mineral filler, while a by-product material (LJMU-A2) was used for the first time in cold mix asphalt with OPC as a supplementary cementitious material in different percentages.

TABLE II
AGGREGATE PHYSICAL PROPERTIES

Material	Property	Value
Coarse aggregate	Apparent particle density, Mg/m3	2.67
	Particle density (OD), Mg/ m3	2.62
	Particle density (SSD), Mg/ m3	2.64
	Water absorption, %	0.8
Fine aggregate	Apparent particle density, Mg/ m3	2.65
	Particle density (OD), Mg/ m3	2.54
	Particle density (SSD), Mg/ m3	2.58
	Water absorption, %	1.7
Mineral filler	Particle density, Mg/ m3	2.57

TABLE III
PROPERTIES OF (C 60 B5) BITUMEN EMULSION

Description	(C 60 B5) bitumen emulsion
Type	Cationic
Appearance	Black to dark brown liquid
Base bitumen	100/150 pen
Bitumen content	60%
Boiling point, ˚C	100 ºC
Relative density at 15 ˚C, g/ml	1.05

TABLE IV
PROPERTIES OF 100/150 AND 40/60 BITUMEN BINDERS

Bituminous binder 40/60		Bituminous binder 100/150	
Property	Value	Property	Value
Appearance	Black	Appearance	Black
Penetration at 25 ºC	49	Penetration at 25 ºC	131
Softening point, ºC	51.5	Softening point, ºC	43.5
Density at 25 ºC	1.02	Density at 25 ºC	1.05

B. Sample Preparation and Conditioning

The design method was based on the method implemented by the Asphalt Institute [19] for designing the new cold asphalt concrete binder course bituminous emulsion mixtures. Incorporation of the OPC and LJMU-A2 by-product material was accomplished over a partial substitution of the conventional mineral filler.

The influence of replacement of conventional mineral filler with OPC and LJMU-A2 was investigated through the indirect tensile stiffness modulus test (ITSM). The substitution of the conventional mineral filler by OPC was conducted in five different percentages (0, 1.5, 3, 4.5, and 6% by dry aggregate weight). On the other hand, LJMU-A2 was used as a supplementary cementitious material in different percentages to activate OPC and at the same time replace a part of it. Additionally, the results have been compared with two types of hot asphalt concrete binder course and with the cold asphalt concrete binder course having limestone dust as filler. All the samples were made and compacted at ambient temperature. Compaction was accomplished by means of a Marshall hammer, with 50 blows to each side of the specimen. At least three replicate specimens were compacted in a Marshall compactor for indirect tensile stiffness modulus tests. Sample

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curing was divided into two stages: the first stage was achieved after 1 day at 20°C, in which the samples are still in the mould; these samples were extracted the next day to prevent their disintegration. Then, the samples were placed in a ventilated oven for 24 hours at 40°C and here stage two was accomplished. This curing technique represented 7-14 days in the field [4]. After that, the samples were placed in the lab at 20°C and ITSM was conducted at different ages, i.e. 2, 7, 14 and 28 days. In addition, the two types of the AC 20 hot mixes, i.e. AC 20 40/60 and AC 20 100/150, were kept at 20°C and tested at parallel ages, i.e. 2, 7, 14 and 28 days, where the laboratory mixing temperatures were fixed at (150-160°C) and (160-170°C) for the 100/150 pen and 40/60 pen respectively.

TABLE V
ITSM TEST CONDITIONS

Item	range
Specimen diameter mm	100 ± 3
Rise time	124 ± 4 ms
Transient peak horizontal deformation	5 µm
Loading time	3-300 s
Poisson's ratio	0.35
No. of conditioning plus	10
No. of test plus	5
Test temperature °C	20 ± 0.5
Specimen thickness mm	63± 3
Compaction	Marshall 50×2
Specimen temp. conditioning	4hr before testing

Fig. 1 ITSM Apparatus machine

III. METHOD

A. Indirect Tensile Stiffness Modulus Test (ITSM)

The indirect tensile stiffness modulus (ITSM) was used to evaluate the effect of supplementary cementing material in OPC mixtures on the mechanical properties of cold mix asphalt. The ITSM test is considered to be a non-destructive test and it will measure the ability of the individual layers of pavement to distribute traffic loads to the layer below. Currently, the stiffness modulus is normally accepted as a very important performance property of bituminous paving materials and it can give an indication of the load-spreading ability of bituminous paving layers.

The test was performed on cylindrical specimens in accordance with BS EN 12697-26 [20] using Cooper Research Technology HYD 25 testing apparatus. The test conditions were as shown in Table V.

B. Water Sensitivity

The effect of using OPC and LJMU-A2 on the moisture damage performance of the cold asphalt concrete binder course was assessed by measuring the stiffness modulus ratio (SMR).

Two sets of samples were prepared with three specimens for each mixture. The first set was tested under dry conditions for each type of mixture where the temperature was set at 20°C. The samples were fabricated and left for 24 hours in the mould before being extracted. Then, they were stored in the lab for 7 days at 20°C before they were tested. Additionally, another set of samples were made and left for 24 hours in the mould and the next day they were extracted and stored at 20°C for 4 days. After that, they were submerged in water and then placed in a vacuum for 30 minutes and then submerged for another 30 minutes. Subsequently, they were submerged in a warm water bath at 40°C for 3 days. The two groups of samples were tested at 20°C, where all samples underwent the indirect stiffness modulus test. The water sensitivity was evaluated by determining the SMR as the ratio of the wet stiffness to dry stiffness, in accordance with BS EN 12697-12: 2008 [21].

IV. RESULTS AND DISCUSSION

A. Indirect Tensile Stiffness Modulus Test (ITSM)

The results of ITSM tests for the OPC substitution are shown in Fig. 2. It is obviously shown that adding OPC as a replacement for the mineral filler generated important development in the stiffness modulus.

The cold asphalt concrete binder course contained ranges of OPC that varied from 0.0% to 6% of total dry aggregate weight. Furthermore, the same figure contains the results of the soft and hard bituminous hot asphalt concrete binder courses.

There was an important increase in the stiffness modulus with the increased percentage of OPC and the ultimate rate was reached by substituting all the limestone filler with OPC over time. In Fig. 3, it can be seen that there was a rise in the rate of stiffness for the cold asphalt concrete mixtures within early ages when the OPC increased. There are two reasons for this enhancement in the ITSM. Firstly, additional binder was generated from the hydration process of the hydraulic reaction of OPC besides the bitumen residue binder. Secondly, there was loss of trapped water through the hydration process of OPC. Nevertheless, the two conventional hot asphalt concrete binder course mixtures do not show noticeable differences in ITSM with time.

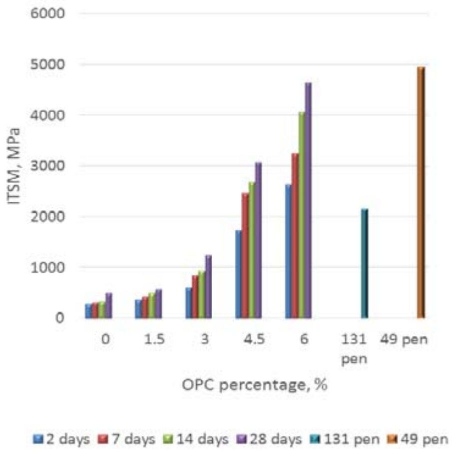

Fig. 2 Influence of OPC on ITSM at 20 °C after 2 days' curing

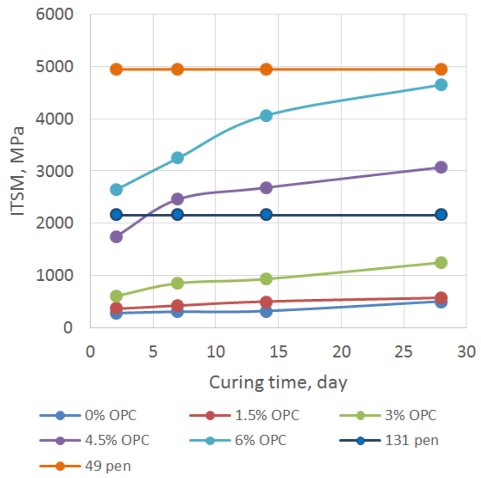

Fig. 3 Effect of curing time on ITSM results

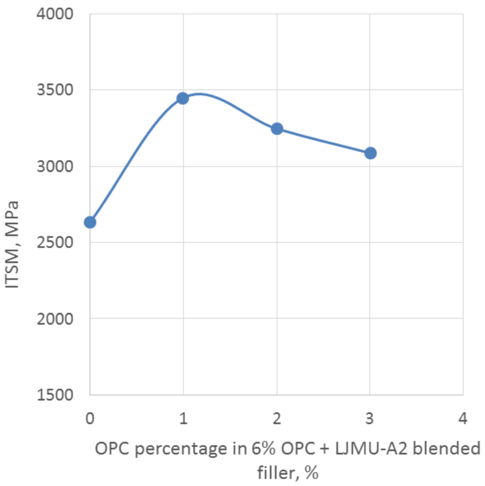

Fig. 4 Effect of replacement of OPC with LJMU-A2 on stiffness modulus of after 2 days' curing

The second improvement was accomplished by using LJMU-A2 in binary filler as a replacement for OPC with various percentages, 0%, 1%, 2% and 3%, by the dry aggregate weight. In Fig. 4, it is obviously shown that the binary blend of 4.75% of OPC with 1.25% LJMU-A2 produced the highest stiffness modulus after 2 days' curing time. Accordingly, a new Binary Blended Cement Filler (BBCF) was submitted.

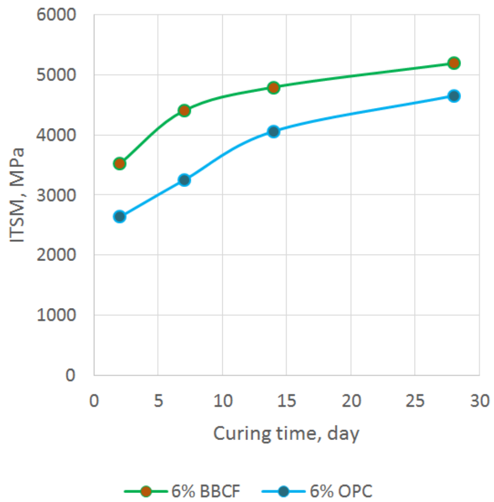

Fig. 5 Effect of curing time on ITSM results for OPC and BBCF mixtures

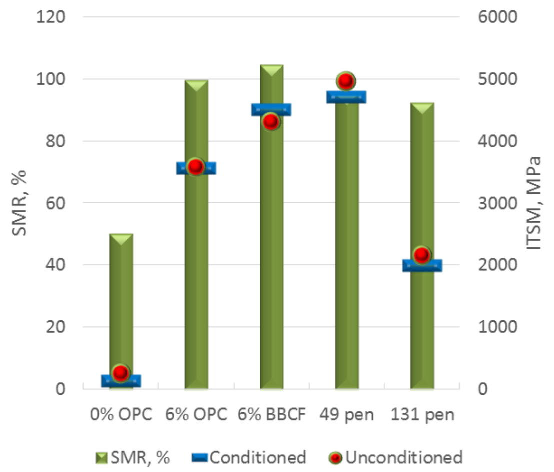

Fig. 6 Water sensitivity results

From Fig. 5, it can be seen that the effect of blending pozzolanic material with OPC, which is rich in calcium hydroxide, leads to improvement in the performance of the OPC. This is because LJMU-A2 contains a high level of silica oxide, which encourages a pozzolanic reaction when it reacts with calcium hydroxide Ca(OH)2 which results from the hydration process. This consequently produces additional calcium silicate hydrate (C-S-H) gels, which provides support and improved strength to the mixtures.

B. Water Sensitivity

The water sensitivity for all the mixtures was measured by determining the SMR in accordance with BS EN 12697-12 [21], to study the effect of both OPC and BBCF replacement of the conventional mineral filler.

It is noticeably shown in Fig. 6 that the SMR with 6% OPC and 6% BBCF is more than 100%. These results were greater than for hot asphalt concrete binder course specimens and met the requirements for bituminous mixtures'. Nevertheless, SMR for the mixtures with 6% BBCF was more than those with 6% OPC. The reason behind that is conditioning the samples at high temperatures activates the hydration process.

V. Conclusion

The following points can be concluded:

1. The substitution of OPC as a replacement for the traditional mineral filler in a cold asphalt concrete binder course enhances the ITSM significantly. Moreover, the application of LJMU-A2 improved the ITSM results of cold mix asphalt. Within a few days, the cold asphalt concrete binder course showed comparative ITSM to the hot asphalt concrete binder course, which was achieved by full filler replacement. However, there was no noteworthy difference for both soft and hard asphalt hot mixtures.
2. The optimum stiffness modulus was found for the optimum blended filler from OPC and LJMU-A2, with a blend of 4.75% OPC plus 1.25% LJMU-A2 to make the new BBCF.
3. The stiffness modulus of the new mixtures developed significantly by replacing the traditional mineral filler with the novel BBCF. Therefore, when compared with the control cold mixtures, the stiffness modulus improved around 12 times after just 2 days' curing for the mixtures containing 6% BBCF. This means that, in terms of stiffness modulus, the performance of mixtures with 6% BBCF is superior to those with 6% OPC.
4. Water sensitivity for mixtures comprising BBCF is more than two times that of untreated cold asphalt mixtures and it is better than mixtures with 6% OPC. Moreover, there is a significant improvement where the stiffness modulus for the conditioned samples is better than that of the unconditioned samples. Furthermore, OPC and BBCF mixtures' results achieve the requirements for the bituminous mixtures and they are better than the conventional hot mixtures, i.e. the soft and the hard types.

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