Studying the mechanical properties of improved cold emulsified asphalt mixtures containing cement and lime

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Abstract. Cold emulsified asphalt mixtures (CEAM) is a cost-effective and ecological technique for bituminous road pavements construction. This investigation evaluates the mechanical properties and durability of CEAM modified using cement and lime as filler replacement. The initial and long-term stiffness modulus, water damage resistance, permanent deformation and fatigue cracking resistance were investigated. To achieve this objective, different laboratory tests were carried out, including stiffness modulus, water damage resistance, wheel tracking and fatigue tests. The results show that incorporating cement and lime in cold emulsified mixtures have an optimistic impact on the mechanical properties and performance. In addition, accelerate the curing time was achieved using such modifiers that are capable of absorbing water.

Keywords: Cement; cold emulsified asphalt mixture; curing time; lime; mechanical properties.

1. Introduction

The growth of road transportation systems, especially in highway engineering, has made many achievements, such as using new methods to apply and control pavement maintenance [1, 2] as well as the additional materials to improve the performance [3-5]. Nevertheless, based on low quality materials, difficulties in quality control, inadequate design and undesirable environmental conditions, the bituminous pavements at an early age have been distressed seriously and various failure modes happened, for example, permanent deformation, water damage, bleeding, pothole, cracking, corrugations, segregation, ravelling, etc [6]. Moreover, it is essential to perform sustainable flexible pavements due to global development in the road pavement industry. In addition, the large consumption of raw and natural materials such as petroleum materials can make energy crisis and ecological problems [7]. Therefore, looking for alternative construction techniques and pavement materials to keep a cost-effective, safe and workable road pavement system has become a necessary need for government requirements and industry. Novel ways are implemented to improve pavement construction and reduce the need for frequent maintenance such as using external additives that enhance the performance and
sustainability of a road system [8-10] and using asphalt emulsion with additives for more sustainable pavement construction [11-13]. Cold emulsified asphalt mixture (CEAM) is a promising bituminous material that has attracted increasing attention due to its cost-effective and eco-friendly behaviours as paving materials during manufacturing, processing and construction stages [4, 14-16]. CEAM consumes a smaller amount of raw materials and fossil fuel and fewer pollutant emissions [17-19]. It consists of unheated aggregates, mineral filler and bitumen emulsion. Using this mixture in flexible pavements construction has mostly been restricted to maintenance [20]. The mechanical properties of CEAM are mainly depending on the curing time and conditions, and bitumen emulsion type [21]. In this sense, different behaviours of such mixture are performed, especially at an early age based on the curing time [22]. Therefore, curing time is considered one of the most important elements that can develop the mixture's strength. It has been stated that CEAM requires from 2 months to 2 years of curing to reach maximum strength [23]. This long curing time causes numerous drawbacks prior to obtaining the final mixture strength. Accordingly, decreasing the curing period of the emulsified mixtures is cost-effective and protecting the environment and construction workers as compared with hot mix asphalt (HMA). Thus, different additives have been used in CEAM technology to fasten the curing procedure and enhance mechanical properties. Cement and lime have been generally added to CEAM in order to improve the engineering characteristics based on the fast bitumen emulsion coalescence that followed by compaction, development of bitumen viscosity and cement hydration [24-26]. The presence of cement in CEAM provides a cured asphalt mixture with excellent mechanical, thermal, and aging resistance properties. Cement hydration retarding is affected by bitumen emulsions in terms of emulsion and emulsifier types [27, 28]. Hydration of cement that changes the modified CEAM properties [29], motivates demulsification and quickens the demulsifying speed. Correspondingly, several investigations have been carried out on the design procedure, long and short terms behaviour and evaluation, and economical and ecological analysis of cold asphalt mixtures [30-34]. Appropriate behaviours of such mixtures have been noticed based on rutting resistance, water sensitivity and cracking in comparison to HMA [35, 36]. CEAM with and without cement have been experimentally studied to estimate the early and long-term strength of such mixes. Oruc et al. [37] reported that CEAM improved with cement CEAM might be performed as a pavement structural layer. Thanaya et al. [38] stated that in addition to the developed engineering properties, including 1-2 % cement in the emulsified asphalt mixture can accelerate the early age strength. Al-Hdabi et al. [39] investigated the impact of cement on cold mix asphalt and concluded enhanced engineering characteristics of cold mix that are equivalent to the traditional hot mix within one day of curing. Using of modifiers in CEAM is to reduce curing time and restore the bituminous mixture properties then recover mixture performance such as stiffness, workability and flexibility [40, 41]. These modifiers have their desirable properties and they are selected based on different factors in terms of materials availability, unit cost, durability, construction policy and so on. Bocci et al. [42] investigated using lime filler in cold mix technology and found that it has considerable ecological advantages. Lime is considered the best modifier in terms of high plasticity [43]. Lime is the ideal modifier in cold mixtures since it is easily reacting with other materials such as water and thus improving the strength of the mixtures. In addition to the load-bearing capability development, it can minimize plasticity and hydration swelling of mixtures. Niazi and Jalili [44] studied the impact of lime on cold mix properties and specified that lime could improve water damage resistance and permanent deformation effects. Kansas Department of Transportation (KDOT) used hot lime slurry as an effective modifier in asphalt mixtures and the findings showed that this modifier could be an active replacement to the traditional filler and type C fly ash. Moreover, the hot lime slurry can improve the mechanical and engineering performance of asphalt mixtures according to the permanent deformation resistance and water sensitivity, and develop tensile strength of such mixture [45-47]. Tarefder et al. [48] carried out laboratory and in-site investigation on lime-modified cold recycled roads to estimate the performance of the cold mix technique. The results stated that cold recycled mixes modified with lime have effective behaviour. Lime is normally used as an active filler to improve the mixture's performance without considerable loss in the mixtures’ flexibility. At the same time, lime has the ability of water absorption from the mix and
thus improve the stiffness of mixtures. Betti et al. [49] evaluated the influence of short-term lime treated cold mixtures. According to the obtained findings, lime was effectively recommended as an active filler. Based on that, this investigation aims to study the early-age strength and long-term behaviour of CEAM with different cement and lime contents. The early-age strength of CEAM was characterized through the indirect tensile stiffness modulus test and moisture damage test, whereas the long-term behaviour was evaluated through wheel tracking and fatigue tests.

2. Research methodology

2.1. Materials

2.1.1. Bitumen emulsion. Cationic slow setting bitumen emulsion (C50B3) with 50% residual bitumen content based on 40/60 penetration grade bitumen was used as a binder for the aggregates. This bitumen emulsion was supplied by Jobling Purser, Newcastle, UK that named Cold Asphalt Binder (CAB50). It was selected as this type has high stability and adhesion.

2.1.2. Aggregates. Virgin crushed granite aggregate provided by Bardon Quarry, Leicestershire, UK was selected for manufacturing CEAM. This selected aggregate consists of asphalt concrete close the graded surface course with a 14 mm aggregate maximum size based on the European Committee for Standardization - Part 1, 2012 [50]. The aggregate grading together with the specification limits are shown in Figure 1.

![Figure 1. Selected aggregate gradation with specification limits](image)

2.1.3. Filler. In this study, limestone dust was utilized as a conventional filler. Cement and lime were employed as filler replacement. The performed cement was quick hardened ordinary Portland cement. The basic parameters of these used fillers were displayed in Table 1.

| Table 1. Properties of used fillers. |
Property Limestone dust Cement Lime

| Property     | Limestone dust | Cement | Lime  |
|--------------|----------------|--------|-------|
| Specific gravity | 2.647          | 3.15   | 2     |
| CaO, %       | 77.82          | 63.49  | 84.00 |
| SiO₂, %      | 17.21          | 21.25  | 2.20  |
| Al₂O₃, %     | 0.00           | 4.74   | 1.02  |
| MgO, %       | 0.89           | 1.02   | 0.44  |
| Fe₂O₃, %     | 0.00           | 4.30   | 1.87  |
| SO₃, %       | 0.01           | 2.93   | 0.34  |
| K₂O, %       | 0.35           | 0.78   | 0.00  |
| TiO₂, %      | 0.19           | 0.36   | 0.00  |
| Na₂O, %      | 2.27           | 0.30   | 0.46  |

2.2. Test methods

2.2.1. Indirect tensile stiffness modulus test. The indirect tensile stiffness modulus (ITSM) test of CEAM with and without modifiers (cement and lime) was applied according to the British Standard [51]. Bituminous mixtures of 1200 g of weight were prepared, mixed and compacted in cylindrical steel molds with 101.7 mm diameter by 63.5 mm in thickness. 50 blows of compaction were performed on each sample surface using Marshall hammer compactor and then (24 hours later) demolded. During the test, a diametrical sinusoidal load is applied to the samples at a constant speed at 20 °C. Three replicated samples were performed for each specific mixture and all samples were cured at lab temperature (about 20 °C). The test diagram is displayed in Figure 2. In this test, the early age strength of all mixtures was evaluated.

2.2.2. Water damage test. Two sets of water damage test samples with each set five replicates of two different conditioning methods were prepared for testing. The samples in the first set were tested using an ITSM test after 7 days of curing at room temperature (about 20 °C). The second saturated conditioning involves 4 days soaking at a 20 °C water bath after that 3 days soaking at 40 °C. The stiffness modulus ratio (SMR), which is retained ITSM water conditioned samples over the ITSM of the dry set, was calculated as an indicator of the water damage [4, 11, 12, 52]. All specimens were tested at 20 °C based on the European Committee for Standardization - Part 12, 2008 [53].

2.2.3. Permanent deformation (rutting) test. To assess the permanent deformation resistance of the CEAM, the wheel track test was performed at 60 °C based on the European Committee for Standardization - Part 22, 2003 [54]. CEAM samples were produced for each mixture type, and the dimensions of each sample were 400 mm × 305 mm × 50 mm. The permanent deformation of each CEAM was determined after 20000-wheel load passes of 0.7 MPa.

2.2.4. Fatigue test. A laboratory experiment was carried out to evaluate fatigue crack resistance of modified and unmodified CEAM mixtures using a four-point beam bending test based on the European Committee for Standardization - Part 24, 2012 [55]. The samples were compacted by a steel roller compactor and tested at a controlled room temperature of 20 ± 1 °C. Long-term curing was applied to the mixtures prior to the testing. The samples were cut by steel saw with the total length, width and height of the prismatic samples of 400 mm, 50 mm and 50 mm, respectively. Fatigue life is determined in terms of the load application number (N) where a 50% reduction in the initial stiffness is reached.

3. Analysis and discussion of test results
3.1. Indirect tensile stiffness modulus

The indirect tensile stiffness modulus (ITSM) of modified and unmodified CEAM mixtures with cement and lime is shown in Figure 2. It can be seen from this figure that the ITSM differs greatly as a result of using cement and lime as substituted fillers to the traditional limestone dust. The conventional CEAM had the lowest ITSM and very long curing time. In the modified mixtures, the mixing ITSM is much better than that of conventional CEAM at all time of curing. All modified CEAM mixtures at one day of curing performed much better than the conventional CEAM mixture after a long time of curing. Accordingly, using cement and lime as filler replacement in CEAM mixture can develop both initial and fully cured ITSM and accelerate curing time. Generally, cement and lime lead to a higher cohesion between the aggregate particles in presence of binder and lower time of curing, indicating that including cement and lime in CEAM provide a positive impact on the early-age strength of such mixture.

![Figure 2. ITSM of different mixes with different curing time](image)

3.2. Water damage

Figure 3 displays the water damage outcomes based on stiffness modulus ratio (SMR). It can be clearly seen that the SMR of the conventional CEAM is only about 50.5%, whereas modified mixtures with cement and lime display significantly higher resistance to water damage. The SMR of cement and lime modified CEAM is around 94.8% and 91.4%, respectively. It indicates the cement hydration during soaking enhanced the strength of mixtures. In general, replacing traditional limestone dust filler with cement and lime develop the soaked ITSM, thus improve the water damage resistance.
3.3. Permanent deformation (rutting)

Figure 4 illustrates the findings of the wheel track rutting tests. It can be realised that conventional CEAM without modification had the highest rut depth value. Inserting cement and lime as modifiers and filler replacement, rut depth values decrease. In other words, including cement and lime enhanced the high-temperature permanent deformation of CEAM.
3.4. Fatigue

Figure 5 summarizes the typical fatigue loading cycles obtained from the prismatic CEAM fatigue test. These results define the fatigue at which the initial stiffness is reduced to 50%. The conventional CEAM mixture had the lowest fatigue life compared to the other modified CEAM mixtures. Cement and lime modified CEAM mixtures had significantly higher fatigue life than the conventional mixture by about 400% and 200%, respectively.

![Fatigue results](image)

**Figure 5.** Fatigue results

4. Conclusion

Different CEAM mixtures produced with and without modifiers were evaluated for different performances using laboratory tests. Conventional CEAM and two modified mixtures with cement and lime were investigated. Based on a series of comparison analysis, the following observations were carried out:

- Incorporating cement and lime into CEAM appeared to improve both the initial and fully cured ISTM and reduce the curing time of such mixture. The use of cement and lime as a substitution to the filler is found to develop the stiffness modulus of CEAM by about 23 times for cement and 4 times for lime after 2 days of curing.
- Replacing traditional mineral filler with cement and lime greatly improve water damage resistance of CEAM mixtures. Adding cement by 6% significantly develop the SMR from 50.5% to 94.8%, and 91.4% in terms of 6% of lime addition, indicating the potential cement hydration during soaking.
- Modified CEAM mixtures with cement and lime were prepared and their performances were evaluated to reduce the effect of the high temperature of the high temperatures in terms of
permanent deformation. Cement and lime modified cold mixtures displayed less rut depth at 60 °C compared to the unmodified CEAM.

- Using cement and lime as modification agents in CEAM to improve the excessive fatigue appeared to be a practical solution. The fatigue life of cold mixtures can be developed and thus service life of the pavement extended when replacing the traditional limestone dust filler by cement and lime.

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