Sustainable Utilization of Lime Kiln Dust as Active Filler in Hot Mix Asphalt with Moisture Damage Resistance

Abstract: The Australian flexible road pavement network is experiencing a considerable degree of reveling and stripping damage in association with moisture. The next generation of hot mix asphalt (HMA) mixtures in Australia needs to have excellent engineering properties as well as higher resistance to moisture damage. Hydrated lime (HL) with a relatively high content of active lime is used in HMA mixtures to improve engineering properties, and particularly to enhance the resistance of HMA mixture to moisture. HL is currently considered a superior mineral filler to crushed rock baghouse dust but it is commercially produced and relatively expensive. Lime kiln dust (LKD) is an industrial by-product which has hydrated lime HMA filler-like properties with similar fineness and a relatively high content of active lime. The lime components in LKD assists in promoting resistance to the stripping common in siliceous acidic aggregates. This project aims to determine an optimum proportion of LKD in an LKD-asphalt binder mixture, based on the properties of viscoelasticity and aggregate adhesion. Dynamic shear rheometer testing and rolling bottle tests were used to evaluate the properties of the LKD-asphalt binder mixtures with varying LKD content. The test results indicated that a 50% LKD content in the LKD-HMA binder mixture provided superior viscoelasticity properties., an acceptable adhesion of asphalt to aggregates was also observed. Last but not the least, a 'cradle to gate' life cycle assessment was carried out to capture the benefits of the use of LKD by-product. This showed that GHG emissions and embodied energy demand could potentially be reduced by 18.5% and 2.4%, respectively if a 50% LKD asphalt binder by mass mixture was used in the LKD-HMA mix..

Keywords: Lime Kiln Dust, Asphalt Concrete, Asphalt Binders, Dynamic Shear Rheometer, Rolling Bottle Test, life cycle assessment

1. Background and Introduction

The construction industry consumes: 40% of natural materials, 40% of the total primary energy, 15% of the world's fresh water resources, and generates 25% of all the wastes and 40 to 50% of green house gas (GHG) emissions [1] ; the design team is thus charged to adopt an environmentally responsible approach to their design solutions and construction materials' specification choices. [1]. Among various major emitting industries, the construction sector offers large abatement opportunities for emission reduction in the short-term due to its economic importance and also opportunities for use of structurally-sound, low carbon intensive materials. In the case of flexible pavements, asphalt (or bitumen), the binder used for the flexible pavement surface material of a multi-layered road pavement system accounts for a significant portion of the total life cycle GHG emission of the total pavement system. An asphalt concrete (AC) mixture (a combination of an asphalt binder and aggregates) is considered a relatively thin surface layer of the road pavement system. The use of asphalt during new road pavement construction and any maintenance stages will result an increase in the overall life cycle GHG emissions of the flexible pavement [1].

This paper highlights both the technical and environmental concerns associated with the use of AC mixture in pavement. AC as a surface material can be referred to hot mix asphalt (HMA) based on the construction process which requires high temperature (around 160℃) to create workable asphalt when mixed with aggregate. Flexible (asphalt) pavements are vulnerable to surface damage due to an increase in temperature, but more severe structural damage is caused by an increase in water damage arising from wetter winters and more frequent intense rainfall events [2]. Water can cause the loss of the adhesive bond between aggregates and an asphalt binder within the AC surface layer and road pavements are damaged because the pavement strength and durability is reduced [3]. This weakening, if severe enough, can result in stripping, which can lead to various forms of HMA pavement distress, including rutting and fatigue cracking. For example, McRobert and Foley [4] highlight a large degree of reveling and stripping damage that has recently occurred in parts of the Great Eastern Highway, Western Australia. This issue has led to the revision of current asphalt mix specifications to be more cognizant to this damage.

Mixtures of HMA have three main components: mineral aggregates; asphalt as a binder; and air voids. In the HMA matrix, asphalt and mineral filler (mineral aggregates passing the No. 200 (less than 0.075 mm) sieve mesh were mixed to form a mastic coating. HMA can be considered as a mixture of mastic-coated aggregates, in lieu of pure asphalt-coated aggregate [5]. Improved mastic properties will result in better moisture damage resistance of HMA. In the early stage of research on the mastic, Richardson [6] investigated several functions in the mastic and proposed that not only just void-filling as originally thought, but also the physico-chemical phenomenon existed in the mastic filler-asphalt system. From the late 1930s, the stiffening effect or reinforcement mechanism of filler in the mastic was focused [7,8,]. Buttlar [9] provided a good explanation of such reinforcement mechanisms. Reinforcement can be divided into three categories: a) volume-filling reinforcement (stiffening resulted from the presence of solid (filler) inclusions into a soft matrix (asphalt)), b) physico-chemical reinforcement (stiffening resulted from interfacial effects between asphalt and filler particles, including absorption), and c) particle-interaction reinforcement (stiffening resulted from interactions between filler particles and altered asphalt). Based on knowledge of how filler plays a role in the performance of HMA by providing reinforcement of the mastic in HMA, this study concentrates on using lime kiln dust (LKD) as an active filler, instead of hydrated lime (HL), a commonly used active filler for improving moisture damage resistance of HMA.

HL has a relatively high content of active lime in the form of calcium hydroxide ($Ca(OH)_2$). HL is generally used in HMA mixtures to improve engineering properties and particularly to enhance the resistance of HMA mixtures to moisture [10]. HL is currently considered to be HMA filler in accordance with ASTM C1097 and AASHTO M303, but it is commercially produced and is an expensive material in HMA. Didier L., et al [11] performed a literature review of HL as an active filler in HMA and noted that HL is an additive that increases HMA durability. The strong interactions between both aggregates and an asphalt binder and a combination of four mechanisms, two on the HMA aggregates and two on an asphalt binder are a reason behind the effectiveness of HL in HMA [11]. HL modifies the surface properties of the HMA aggregate, allowing for the development of surface composition and increased roughness favourable to asphalt binder adhesion. HL also treats existing clay particles adhering to the aggregate surface, inhibiting their detrimental effect on the mixture. HL reacts chemically with acids in the asphalt binder, which in turn slows down age hardening kinetics and neutralizes the effect of the "bad" adhesion promoters present inside an asphalt binder, enhancing the moisture resistance of HMA mixtures.

Like asphalt, HL is an energy intensive material to produce and will increase the overall GHG emissions and costs, therefore, there is a need for consideration of an alternative materials. As a result, the road construction industry has also incorporated a wide variety of by-products into HMA road pavement in order to reduce CO_2 emissions. For the industrial by-products, Kahdhal [12] stated that a range of by-products have potential for use in HMA for road construction purposes. Previous studies [13-21] demonstrated that potential industrial by-products for HMA included fly ash and bottom ash, from coal fired power plants. Fly ash can be used as a mineral filler in HMA applications [22]. Generally, fly ash will typically meet specifications mineral fillers for gradation, organic impurities, and plasticity and fulfil the main function of HMA mineral filler in increasing the stiffness of the asphalt mortar matrix, improve the rutting resistance of pavements, and the durability of the mix [20]. An et al. [23] demonstrated bottom ashes could also be utilized in HMA by partial replacement of fine aggregate in the HMA aggregate matrix, but the bottom ash behaved like lightweight aggregates which contain relatively high porosity; thus, it required higher amount of asphalt binder in the HMA mixture. Since FA is mainly used as a replacement for cement in concrete, and its supply is limited, other potential by-products to replace FA need to be explored.

Lime kiln dust (LKD) is another industrial by-product which has HMA filler-like properties in both fineness and a relatively high content of active lime. LKD can be comprised of up to 30-50% calcium oxide (CaO) and 30-50% calcium carbonate ($CaCO_3$) [24]. Therefore, the lime components in LKD could assist in promoting resistance to the stripping that is most common in siliceous acidic aggregates.

Previous studies [14,25] showed that LKD can be effectively used as active filler in HMA mixtures and would offer higher sustainability performance in terms of cost saving and resource conservation for future generations. (this is an opinion and unsubstantiated).

Jiupeng Z, et al [26] demonstrated that the component of calcium oxide (CaO) in the CaO-asphalt system plays a major role in the superior rheological properties of the mastic. The significant amount of CaO in HL and LKD could lead to greater stiffening of the mastic, resulting in a better moisture damage resistance of HMA mixture with inclusion of HL or LKD.

In these aforementioned studies, LKD was considered as a very small portion of aggregates of the whole HMA mixture. On the basis of high CaO content of LKD, the conclusion was drawn that it could enhance the overall performance of HMA. However, the effect of LKD to the particular moisture damage resistance of HMA through some fundamental investigations was not performed in these studies. Therefore, this current research has applied dynamic shear rheometer and rolling bottle test to determine the optimum amount of LKD for maximizing the moisture damage resistance of HMA mixtures. These tests investigate the effects of LKD to the visco-elastic properties of LKD-asphalt binder mixtures and the coating ability between binders and aggregates.

The estimation of optimum amount of LKD in HMA mixture would determine the environmental and sustainability benefits associated with the replacement of HL with LKD in HMA mixture.

Studies have been performed to assess the sustainability of the use of industrial by-products for infrastructure and chemical industries. The conversion of the NOx (i.e. a generic term for the nitrogen oxides) by-product to fertilizer was found to offer overall savings of 46%, 274% and 583% reduction in GWP, acidification potential and eutrophication compared to conventional fertilizer [27]. Nath et al [28] found that about 36%–43% of carbon footprint and 36%–38%of embodied energy consumption can be avoided for different concrete covers due to replacement of 40%cement with fly ash. The sustainability assessment of Biswas and Cooling [29] shows that the replacement virgin sand and limestones with red sand (i.e. by-product of bauxite residue) for construction purposes could potentially offer economic, social and environmental benefits. Line 136 to 146 is completely irrelevant to this study.

The aim of this study is to assess and demonstrate the incorporation of LKD into HMA mixture in order to increase the overall performance, concentrating on moisture damage resistance. Furthermore, the life cycle GHG emission of HMA mixture using LKD as a main constituent compared to HMA mixture with HL is considered.

To achieve the aim, the specific objectives are to:

- Determine an optimum for LKD filler in the mastic based on laboratory investigations.
- Perform an estimation of carbon footprint or life cycle GHG emissions and embodied energy demand for the replacement of HL with LKD in HMA mixtures.

Firstly, this paper demonstrates an evaluation of an optimum ratio of LKD and asphalt binders that show moisture damage resistance. Sophisticated test results from dynamic shear rheometer (DSR) and rolling bottle test (RBT) were used as a basis to properly determine an optimum ratio of LKD and asphalt binder mixtures. DSR tests were performed to detect rheology properties of LKD and asphalt binder mixtures in a form of a master curve. RBT were also carried out to detect a degree of affinity between aggregates and LKD and asphalt binder mixtures. Secondly, it was estimated the amount of carbon footprint or life cycle GHG emissions and embodied energy demand that could be avoided due to use of LKD as a replacement of HL in HMA mixtures. ISO 14040-44 guideline for life cycle assessment were applied to calculate these parameters in this study.

The innovation in this work lies in the potential to rationally evaluate the possibility of using a by-product into the road pavement construction in ways that fundamental technical approaches were used in conjunction with the sustainability evaluation through the carbon foot bring figure. Within this study, a proper amount of LKD into HMA mixtures was determined based on the combined results of DSR tests and RBT. This is to capture effects of LKD to the visco-elastic properties of LKD-asphalt binder mixtures and the coating ability between binders and aggregates. This determination is unique in the field of pavement engineering. Furthermore, the sustainability evaluation was merged to the technical evaluation to create the definite evaluation of using LKD in HMA mixtures.

2. Methods and materials

This section is divided into two parts. Firstly, an experimental procedure was developed to determine an optimum ratio of LKD and asphalt binder that is moisture damage resistant. Secondly, a life cycle assessment was conducted to determine the environmental implications of the use of LKD as an asphalt filler. For quantifying the environmental implications of the use of LKD in HMA mixtures, GHG emissions and embodied energy consumption indicators were estimated in the LCA [1].

2.1 Experimental procedure

2.1.1 Materials

Aggregate: The aggregate used in this study was sourced from quarries around Perth to replicate the physical aggregate properties used in asphalt pavement in the Perth metropolitan region. Petrographic reports outlining the aggregate mineralogy shows that the aggregates sourced for this study has a composition of 39%Quartz and 26% K-Feldspar.

Asphalt binders: The specified asphalt binder types of C170 and C320 were used in this study following Standard Australia [30].

Active fillers: As active fillers of HMA, both HL and LKD were used in this study as reference (normally used) and study materials, respectively.

HL is manufactured material obtained by treating quicklime with enough water to satisfy its chemical affinity for water. Quicklime is manufactured through calcination of high carbonate shells and at elevated temperatures. In this study, industrial hydrated lime was used as a reference active filler as it was specified by Western Australia Mainroads (MRWA). HL has a typical bulk density of 375 kg/m^3 [31]. Cockburn Cement's MSDS states HL is composed of 80 % – 95 % Calcium Hydroxide ($Ca(OH)_2$) with 95 % of particles passing through a 75-micron sieve [32].

LKD is the dust collected by the baghouse filters in a lime kiln during the calcination process. LKD used in this study was sourced from Cockburn Cement Western Australia with their suggested main composition and concentrations of CaO of 40%-60% and $CaCO_3$ of 40%-70% [33].

2.1.2 Tests

DSR tests:

For the sample preparation process of DSR tests, original binders of C170 and C320 were mixed with HL and LKD using a high shear mixing machine. The binders were kept in 250 cc containers and left in the oven at 160℃ temperature (mixing temperature) overnight. A percentage of HL or LKD by mass was directly added to a binder container almost immediately after it was taken from the oven to assure a 160℃ mixing temperature. Then, the mixing process was performed until the HL or LKD-binder mixtures reached their (stable) consistency. The HL or LKD-binder mixtures were produced batch by batch for the DSR test without storage to avoid the sedimentation which would occur.

The DSR test is generally performed to observe the rheology properties of asphalt binders through a series of dynamic shear modulus values and its corresponding phase angles in a range of test temperatures between 4 and 88°C with a speed of rotation of 10 rad/sec [34]. The liner viscoelastic properties of asphalt binders can be determined from the DSR test. Because asphalt binder is a viscoelastic in nature, its phase angle normally falls in between 0° and 90°. A phase angle at the value of 0° depicts the characteristic of an elastic solid and a phase angle at the value of 90° represents that of a viscous liquid. In this study, based on the procedure of the test, the complex shear modulus (G*) and the phase angle (δ) were determined with varied test temperatures of 40, 50, 60, and 70°C and frequencies from 0.1 to 10 Hz (i.e., the speed of rotation) to form a data set for constructing a master curve. The master curve is a single smooth curve which aligns multiple temperatures of dynamic modulus values in frequency domains. This curve represents the dynamic modulus values over an observed range of temperatures and frequencies. It is normally derived from the complex modulus which consists of two parts; the real value part represents the elastic stiffness, and the imaginary part represents the internal damping [35,36]. The dynamic modulus is the absolute value of the complex modulus which is derived from a continuous sinusoidal (or haversine load), without a rest period.

For the master curve generation, in this study, the original binders of C170 and C320 as well as the HL or LKD-binder mixtures were characterised according to the master curve of the dynamic shear modulus (|G*|) with regard to varying temperatures and frequencies. The properties and the performance of asphalt as a HMA binder strongly depend on temperature and frequency (time). Consequently, the multiple lines of a set of dynamic moduli corresponding to an array of different temperatures in the frequency domains shown in Figure 1 can be observed. However, it would be much better to represent the performance of an asphalt binder in terms of a dynamic shear modulus (|G*|) through a single smooth line, rather than multiple lines, in association with the Time-Temperature Superposition principle (TTS) [35]. TTS relies on a shift factor, $a(T)$ to be multiplied by frequencies, equation (1), to align multiple lines of different temperature correspondence into one temperature reference line, which is called the master curve. This study chose the Williams-Landel-Ferry (WLF) equation, equation (2), as a shift factor function.

$$\log f_r = \log f + \log[a(T)] \quad (1)$$

$$\log[a(T)] = \frac{-a_1(T-T_R)}{a_2+(T-T_R)} \quad (2)$$

Where f_r represents reduced frequency (Hz); f, frequency (Hz); a(T), shift factor; T_R, reference temperature (°F); T, temperature (°F); a_1, a_2, fitting coefficient. Figure 1 demonstrates the master curve after shifting from various temperatures to be one smooth curve at a reference temperature on a frequency domain.

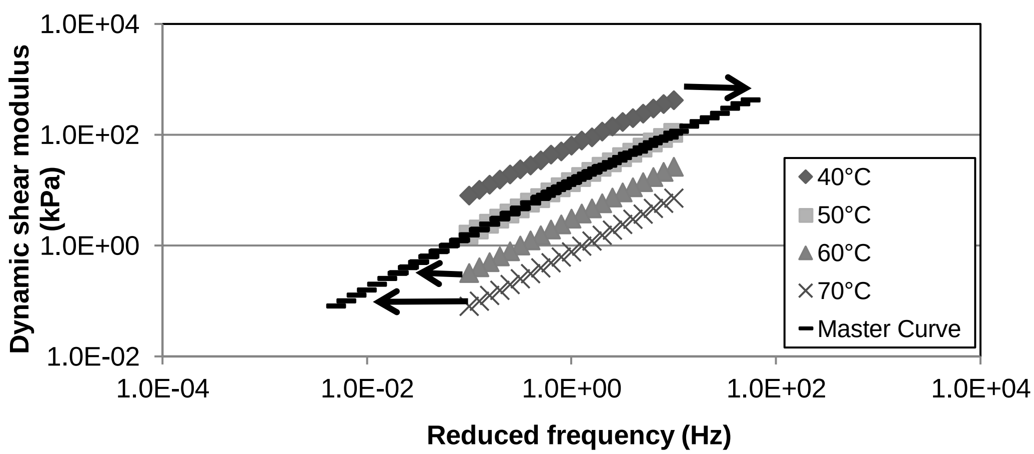

Fig 1. Dynamic modulus master curve.

Rolling Bottle Test (RBT). RBT used in this study was performed in accordance with the standard of EN 12697-11:2012(E) (EN 12697-11 2012). It is the European Standard specifying procedures for evaluating a degree of the affinity between aggregate and asphalt binders. This study used the methods of EN12697 to determine the affinity between study aggregates and LKD-asphalt mixtures and its influence on the susceptibility of the combination to moisture damages such as stripping. In the method of RBT, the affinity can be represented with visual registration of the degree of asphalt binder coverage on uncompacted asphalt binder-coated aggregate particles after storage in water (EN 12697-11 2012). The study aggregate with a size range of 8-11 mm was prepared at 510 g (for a batch of three test bottles) to reach a completely dry condition after placing in a ventilated oven with a controlled temperature of 110°C for 24 hours. Then this dry aggregate was mixed with a 3% binder content of study binders (C170, C320 and LKD-asphalt binder mixtures) at a mixing temperature of 160°C. After mixing, a mixture was allowed to cool down to a room temperature. The asphalt binder-aggregate mixture after cooling was then transferred to the test bottles filled with approximately 50% by volume with distilled water with a temperature of 5°C. The test bottles containing water and mixture were then installed on the bottle rolling machine and the rolling process was commenced. At 6 and 24 hours of rolling, the aggregate particles coated with an asphalt binder were taken out of the bottle to estimate the average degree of binder coverage by visual observation. Visual observation was according to the reference images for estimation of degree of binder coverage as shown in Figure 2. Pictures of RBT conducted in this study are exhibited in Figure 3. It should be noted that to avoid personal bias during visual inspections of RBT tests, the visual inspections were performed with at least three inspectors to get agreement on the degree of particle coating for each test. A series of test result values of these RBT tests were average values of a batch of three test bottles for a given ratio of study binders.

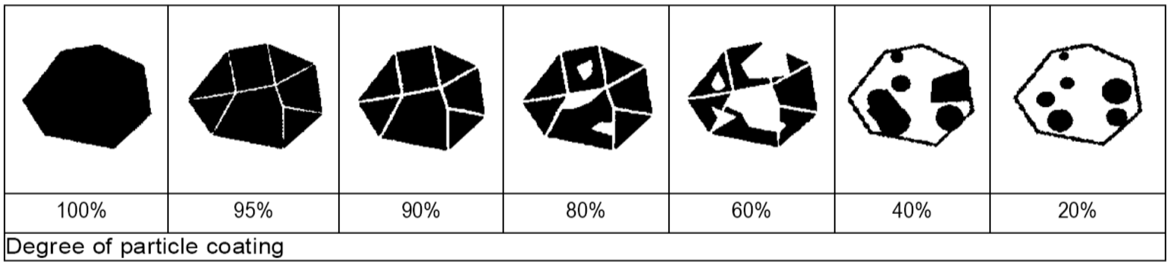

Fig 2. Graphical help of assessment of the degree of coating (Matin Istonbul 2012).

Fig 3. Pictures of RBT of this study.

2.2 Carbon footprint and embodied energy demand assessment

A life cycle assessment (LCA) approach has been applied to estimate carbon footprint and embodied energy consumption of the asphalt concrete mixtures following the guidelines of ISO14040-44 [37]. ISO14040 consists of four steps, namely: goal and scope, inventory analysis, impact assessment and interpretation.

The goal of this LCA is to evaluate the carbon footprint and embodied energy demand of the production and use of asphalt concrete mixtures. Six asphalt concrete mixes, as given in Table 1, were considered for LCA analysis: a control asphalt concrete mix with 100% hydrated lime, five asphalt concrete mixes with 10%, 20%, 30%, 40% and 50% LKD as a filler material.

The system boundary of this concrete LCA includes the mining to use stages of the product life cycle. This consists of several stages including mining of raw material, manufacturing and processing of construction materials, transportation of these materials to the asphalt concrete mix plant and the production of asphalt concrete. The downstream stages including transportation of asphalt concrete to pavement site, haulage of AC mixture in-place project, paving and rolling, maintenance and end of life stages have been excluded as the experimental results of these stages are not currently available. This is why this LCA is termed as a streamlined LCA following Mohammed et al.[27].

The functional unit of this study is 1 m^3 of asphalt concrete mix. A life cycle inventory analysis was done to estimate energy and materials used during the aforementioned stages of asphalt concrete mixes. Table 1 shows the LCI consisting of inputs, including course aggregates, fine aggregates, hydrated lime, LKD, bitumen, transportation and electrical and thermal energy consumption for six asphalt concrete mixes which were pre-requisites to carry out a life cycle impact analysis.

Inputs of life-cycle inventory data in Table 1 were entered into SimaPro 8.2 LCA software [38]; application which requires relevant materials to be linked to an Australian libraries or emission databases to represent the Western Australia's (WA) situation. Where libraries did not exist, new libraries were developed from similar LCA studies. The emission factor databases include all upstream emissions and embodied energy demand of these inputs. The Intergovernmental Panel on Climate Change -IPCC2007 method was used to calculate global warming potential (GWP) of these mixes [39]. The cumulative energy demand method was used to estimate their embodied energy demand.

Equation (3) presents the conversion of masses of different types of GHGs associated with the production and use of material and energy inputs into GWP, which is a single carbon dioxide-equivalent metric (CO_2 e-) [19].

$$GWP\ (CO_2\ e -) = \sum_{i=1}^{i=N} \sum_{j=1}^{j=M} I_i EF_{ij}\ x\ CF_j \quad (3)$$

where, I is the amount of an input

i :1,2,…..N; type of inputs (e.g. aggregates, hydrated lime, transportation, electricity, heating)

EF_{ij} : Emission factor = Amount of emission of GHG type ‘j’ per kg of input of type ‘i’

CF_j : CF_1, $CF_{2, \ldots\ldots}$ CF_M; characterization factors of GHGs (e.g. 1 for CO_2, 28 for CH_4, 265 for N_2O)

The inputs in the life-cycle inventory have been multiplied by the corresponding energy demand values to find out the embodied energy demand of asphalt concrete mixes, which is expressed as follows [37]:

$$EE_{total} = \sum_{i=1}^{N} I_i\ x\ EE_i \quad (2)$$

where, EE_i is the embodied energy demand of an input i.

Table 1
Life cycle inventory

Composition of asphalt concrete Mix	With HL	With LKD					Approximate distance between source to lab (km)	Location of material source
		10%	20%	30%	40%	50%		
Density (tonnes/m^3)	2.444	2.456	2.456	2.456	2.456	2.456	-	
Materials								
Course Aggregate (kg/m^3)	1,372.49	1,392.55	1,385.18	1,377.82	1,370.45	1,363.08	59.50	BGC Quarry, Great Southern Highway, Western Australia 6556, Australia
Fine Aggregate (kg/m^3)	915.00	928.37	923.46	918.54	913.63	908.72	59.50	-ditto-
HL (kg/m^3)	34.31	-	-	-	-	-	27.60	Cockburn Cement, Lot 242 Russell Road East, Munster WA 6166, Australia
LKD (kg/m^3)	-	12.28	24.56	36.84	49.12	61.40	27.60	-ditto-
Bitumen (kg/m^3)	122.20	122.80	122.80	122.80	122.80	122.80	18.20	Sami Bitumen Technologies, Cnr Birksgate & Port Beach Road, North Fremantle WA 6159, Australia
Transportation								
transportation of raw material to hot mix plant (tkm)*	139.28	140.67	140.28	139.89	139.49	139.10	-	
Energy								
Electricity consumption for preparation and mixing (kWh per tonne)	10	10	10	10	10	10	-	
Heat energy consumption for preparation and mixing (MJ per tonne)	300	300	300	300	300	300	-	

*tkm = tonne kilometer travelled by an input to asphalt plant

3. Results and discussion

3.1 DSR

In Figures 4 and 5, it can be seen that the dynamic shear modulus of the asphalt binder C170 and C320 mixed with all fillers is higher than the original asphalt binders and an increase in modulus is proportional to the amount of LKD added (i.e., the more amount of filler is added, the stiffer binder is obtained). Moreover, it is observed that the asphalt binders mixed with HL results in the higher modulus than the one mixed with LKD at a replacement level of 30%. It was noted that filler types affect the stiffness of an asphalt binder.

With consideration of a mixture of the asphalt binders C170 or C320 and 30%HL as a reference material (i.e., 30%HL is a normally used HL content for a specified better performance asphalt concrete for Western Australia), it could be seen that for both asphalt binders of C170 and C320, LKD-asphalt binder mixtures of LKD contents of 40% and 50% exhibit the equal and higher dynamic shear modulus values over a target range of reduced frequencies. Based on these DSR results, promisingly, the LKD contents of 40% and 50% could be candidate LKD ratios for asphalt concrete mixtures.

3.2 RBT

Figure 6 shows that the degree of binder coverage of the asphalt binder C170 mixed with all fillers is higher than the original asphalt binders. An increase in degree of binder coverage is proportional with the amount of LKD added (i.e., the more amount of filler added, the better affinity and the lower moisture susceptibility of the binder). Affinity is improved, and the moisture susceptibility could be reduced with an addition of more filler content. Moreover, it is observed that the asphalt binder mixed with HL results in the higher degree of binder coverage than the one mixed with the same amount of LKD (i.e.30%). For example, different degrees of binder coverage for the same proportion (i.e. 30%) of filler (i.e. LKD and HL), it could be demonstrated that types of filler affect the affinity and the moisture susceptibility of asphalt binders. In Figures 6 and 7, the similar findings can be seen for those of C320.

3.3 Determine the optimum portion of LKD in an LKD-asphalt binder mixture

According to the test results shown, adding more filler may improve the properties of asphalt binders (e.g., better affinity, and lower moisture susceptibility). As a result, the 50% LKD content was selected to be an optimum portion of LKD in the asphalt concrete mixture with better moisture damage resistance. This is because it can provide the best dynamic modulus and the best affinity with the study aggregate. Asphalt binders with much higher LKD content can cause highly viscous asphalt binder with less workability for construction purposes, a compromise between the service ability and the overall property of asphalt binders.50% of LKD added is the optimum portion of LKD in an LKD-asphalt binder mixture based on the study results.

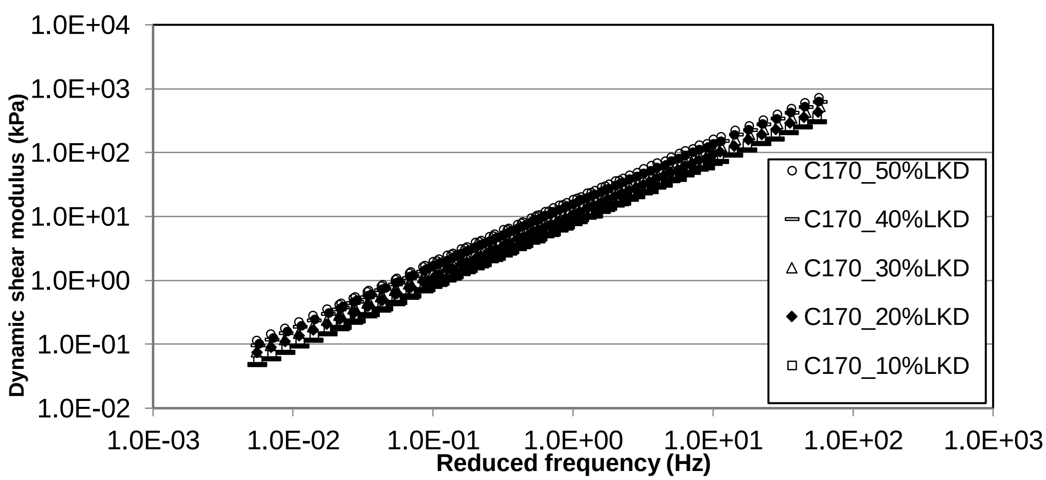

Fig 4. Dynamic shear modulus of the original asphalt binder C170 and all the asphalt binder mixed with fillers.

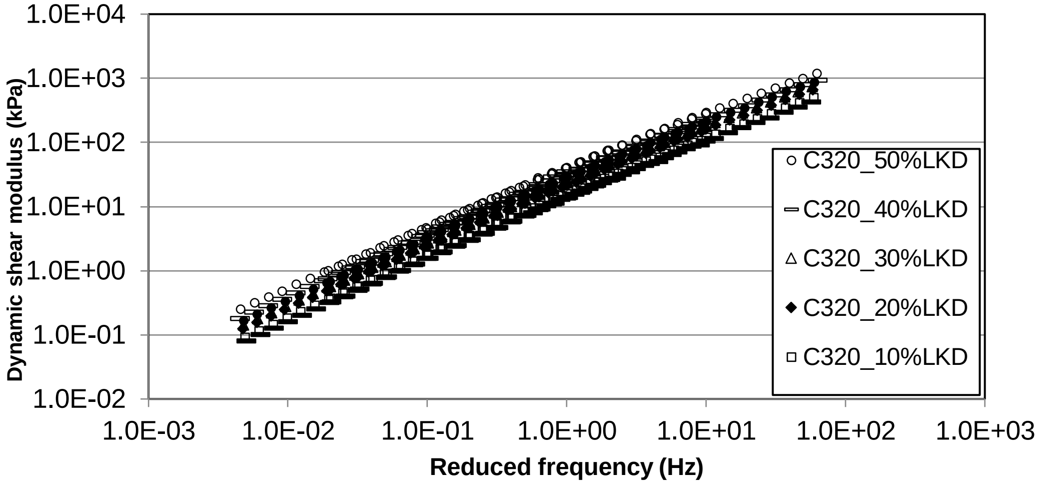

Fig 5. Dynamic shear modulus of the original asphalt binder C320 and all the asphalt binder mixed with filler

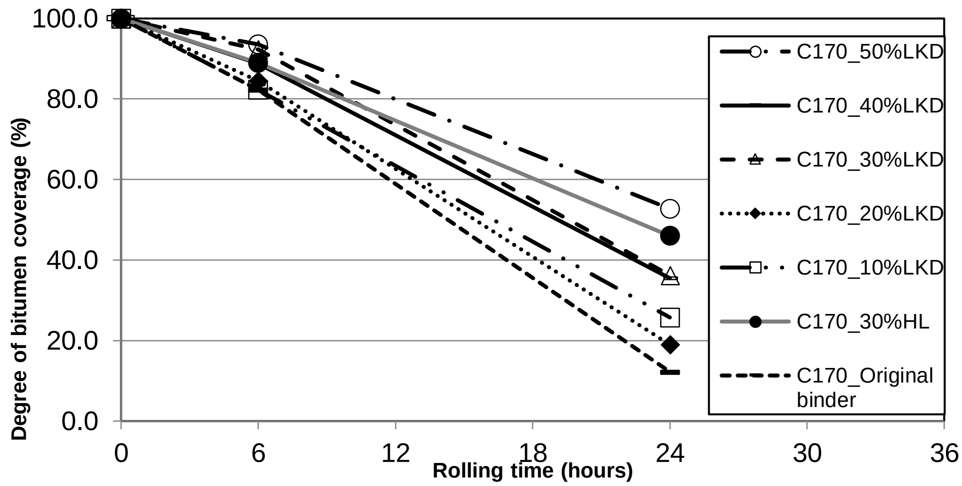

Fig 6. Degree of bitumen coverage of the original asphalt binder C170 and all the asphalt binder mixed with fillers.

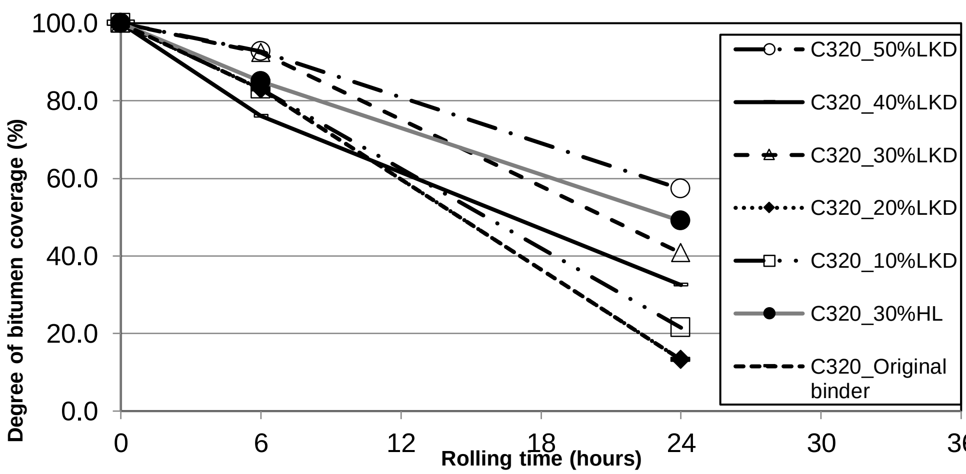

Fig 7. Degree of bitumen coverage of the original asphalt binder C320 and all the asphalt binder mixed with fillers**.**

3.4 Environmental implications of the use of LKD in asphalt concrete mix

A 'cradle to gate' life cycle assessment carried out to capture the environmental benefits of the use of LKD in HMA shows that GHG emissions and embodied energy demand could potentially be reduced by 18.5% and 2.4%, respectively if LKD, which is 50% of bitumen, is used in HMA mixtures (Figures 8 and 9). The increase in LKD in asphalt concrete (i.e. from 10% LKD to 50% LKD) slightly increases both GHG and embodied energy demand savings. This can be explained by the fact that the amount of energy- and carbon-intensive materials like course and fine aggregate in the asphalt concrete mix decreases with the increase in LKD (Table 1). This has other environmental benefits as the use of higher amount of LKD in HMA mixtures would reduce the amount of residue storage area of the cement factory (we do not mine land deposits for quicklime)(we are using old quarries for LKD disposal so no biodiversity loss)

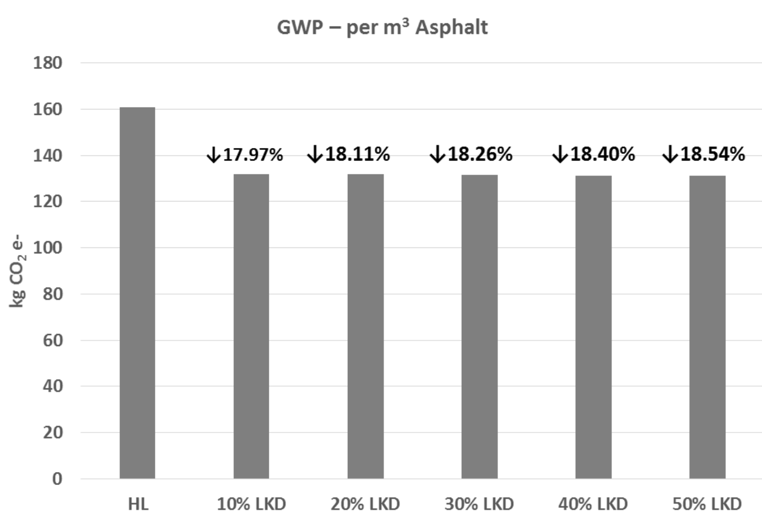

Fig 8. GWP saving potential of asphalt concrete mixes using LKD

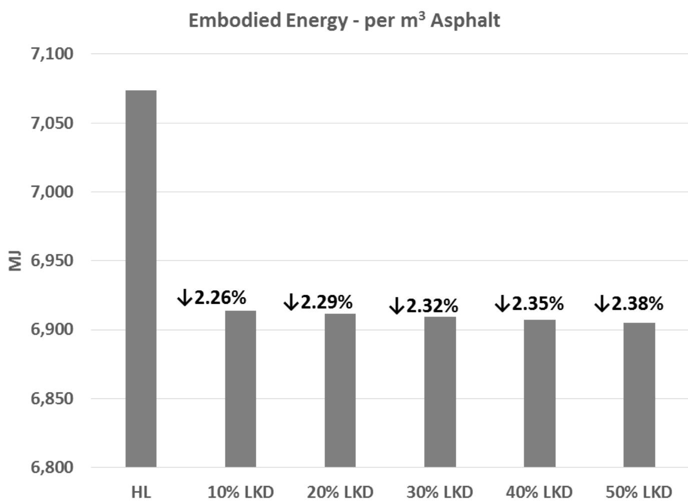

Fig 9. Embodied energy demand saving potential of asphalt concrete mixes using LKD

4. Conclusions and recommendations

This study aims to evaluate an optimum content of LKD in HMA based on the performance of LKD-asphalt binder mixtures through their rheology properties by the DSR tests and ability to coat an aggregate by the RBT tests. The test results indicate that a 50% LKD content by mass was an optimum ration between the mixtures of LKD and study asphalt binders of both C170 and C320. The LKD-asphalt binder mixtures provide good viscoelasticity properties based on a master curve series of the LKD-asphalt binder mixtures. Based on RBT test results, higher LKD contents in the LKD-asphalt binder mixtures resulted in better asphalt (bitumen) coverage for both study binders (C170 and C320). Furthermore, the use of a maximum amount of LKD (i.e. 50% of asphalt binder) in the HMA mixture could potentially reduce GHG emissions and embodied energy demand by 18.5% and 2.4%, respectively. Future research will consider the analysis of socio-economic implications of the use of this cement factory by-product as asphalt filler.

The addition of 50% LKD to normally used asphalt binders (e.g., C170 and C320) can definitely result in significantly higher viscosity. This would lead to less workability of construction (i.e., compaction). Proper mix design processes are strongly required to evaluate the suitability of mixing 50% LKD-asphalt binder mixture with a given aggregate to form satisfying asphalt concrete with LKD. All important properties of a target void ratio, a density, values of stability and flow based on the Marshall method would need to be carefully determined to assure that all asphalt concrete requirements of volumetric and strength properties as well as workability still can be achieved with the addition of 50% LKD to a HMA mixture.

Finally, this study overcomes the uncertainty associated with the use of empirical results of LKD use in HMA as active filler by conducting fundamental experiments that determines the rational portion of LKD in HMA for maximizing the moisture damage resistance of HMA.

5. Acknowledgements

The authors wish to express their gratitude Cockburn Cement for the financial support of this study, under the Cockburn Cement-Curtin University research project, conducted at the Department of Civil Engineering, Curtin University. Thanks to Research Assistants Sarayoot Kumlai and Krishna Lawania for their help in the experimental and life cycle assessment parts of the research, respectively.

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