Temperature Dependency of the Stiffening Effect of Hydrated Lime in Stone Mastic Asphalt (SMA) Mixtures

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Abstract. The effect of hydrated lime (HL) on the stiffening effect of bituminous mixtures is mainly driven by a physical phenomenon derived from the higher Rigden Air Voids (RAV) of HL in contrast to other filler types commonly used in bituminous mixtures such as granite and limestone. The stiffening effects of HL at room temperature for some mixture types have been reported in the literature but the knowledge of the effects on Stone Mastic Asphalt (SMA) mixtures is still limited. Similarly, the temperature-dependency has been theorised in the literature but scarce experimental evidence is currently available. As a consequence, this research focuses on studying the effects of a wide range of temperatures on the stiffening effect of SMA mixtures with HL. Indirect Tensile Stiffness Modulus (ITSM) testing was used in order to assess the stiffness properties of SMA mixtures manufactured with limestone aggregates, a conventional 30/45-penetration grade bitumen, and the addition of HL as a partial replacement of limestone filler (LF). The bitumen to filler ratio was kept as 1:1 for all manufactured mixtures. The results indicated: (*i*) a clear temperature-dependency of the stiffening effect of HL, which is more prominent at intermediate temperatures (20°C and 30°C). (*ii*) The percentage of added HL and the average stiffness of the specimens had an approximately linear correlation. (*iii*) The stiffening effect is less prominent at the lower and higher temperatures considered. (*iv*) The partial replacement of LF by HL produced stiffer mixtures than those without replacement, which suggests improved mechanical response of these SMA mixtures.

Keywords: Stiffness, Hydrated Lime, Temperature Dependency, Stone Mastic Asphalt.

1 Introduction

Hydrated lime (HL) is a fine-white powder, produced from limestone rocks, which was originally used as a filler for bituminous mixture production in the 1950s and it was mainly used for enhanced bitumen-aggregate adhesion. In the 1970s, during the petroleum crisis in the USA, a general decrease in the quality of bitumen induced a higher susceptibility of asphalt pavements to moisture damage and frost. By then, after thorough investigation and field testing, HL was found to be the most effective additive to limit moisture damage which led to a wide use in the USA. In fact, about 10% of current bituminous mixtures produced in the USA incorporates HL. Due to extensive research, HL is now known to provide additional benefits to the mixture performance. Specifically, according to Lesueur et al. [1], HL is considered as an *active filler* due to its ability to: (1) reduce bitumen chemical ageing by delaying the chemical oxidation process; (2) stiffen the mastic and mortar which improves rutting resistance, and (3) increase the resistance to fatigue cracking due to a mechanism that helps delay crack propagation. From the physical point of view, the *active* nature of HL is partially explained by the higher Rigden Air Voids (RAV) of HL in contrast to other filler types, which are related to the porosity of the dry compacted filler and leads to increased stiffening effect of the mastic and the mixture. Thereby, the use of HL promotes increased strength of the bituminous mixtures with positive performance implications [2]. This stiffening effect has been theorised to be more pronounced at intermediate testing temperatures [1], but very limited experimental data is currently available in the literature to corroborate this theory in terms of the temperature-dependency of this HL effect.

Based on a recent literature review by [3], more comprehensive studies on bituminous mixtures are required in order to understand the effects of HL and its mechanisms of action with specific materials, mixture designs and testing conditions across Europe. Furthermore, although HL has proven benefits for bituminous mixtures, particularly in France and the Netherlands, its application in other European countries is still lagging in comparison to the USA. It is therefore required that current investigations should expand knowledge about HL in the European context. In consequence, this paper presents an experimental analysis of Stone Mastic Asphalt (SMA) mixtures with incorporated HL produced with locally available materials and testing protocols in the United Kingdom. Indirect Tensile Stiffness Modulus (ITSM) testing was used in order to assess the stiffness of the SMA mixtures. To contribute to some of the gaps in current knowledge, the main aims of this investigation were to assess the temperature-dependency of the stiffening effect of HL, and to determine the correlation of the HL content and the stiffness modulus in SMA mixtures.

2 Materials and Methods

2.1 Materials

The SMA mixtures were manufactured with limestone aggregates, 30/45 penetration grade bitumen, and incorporated HL as a partial replacement of limestone filler (LF) at concentrations of 0%, 1%, 2%, and 3% by total weight of mixture. The bitumen to filler ratio was kept as 1:1 for all mixtures produced.

2.2 SMA Mixture Design

SMA is a durable surfacing material suitable for use in urban streets and highways. It is composed of a high proportion of coarse aggregate that withstands permanent deformation and is typically composed by bitumen, aggregates, filler and additives (e.g., fibres). Typical SMA is composed of 70-80% coarse aggregate, 8-12% filler, 6-7% binder and 0.3% fibre [4, 5]. SMA mixtures with a nominal maximum aggregate size of 10mm were manufactured in accordance with BS EN 13108-5:2016 Standard [6]. The manufacturing and compaction temperatures are based on bitumen viscosities and these were 165±5˚C and 145± 5˚C, respectively. The aggregates and bitumen were heated for a minimum of 8h and 3h, respectively. HL was added to the dry aggregates in the mechanical mixing drum, where these were subjected to a mixing time of 30 seconds. Immediately afterwards, the bitumen was added and all components were mixed for 3 minutes. For compaction, a roller compactor with smooth steel surface was used to simulate the commonly used compaction method for asphalt wearing courses in the field. Roller compacted slabs were produced with 306x306x60 mm^3 dimensions, designed to a target air voids content of 4%. Six cylindrical specimens were cored from the slabs, removing 10 mm from top and bottom in order to reduce the scattering in air voids content along the specimens' height and produce smooth surfaces. The final specimen geometry was set as 100-mm diameter and 40-mm thickness.

2.3 Determination of Stiffness Modulus

Stiffness is defined as the resistance to deformation of a given material when subjected to external loading and it constitutes a valuable parameter for purposes of designing and characterisation of bituminous mixtures as it provides understanding of the mechanical properties and performance-related characteristics [7]. Testing was carried out using the Nottingham Asphalt Tester (NAT), with Indirect Tensile Stiffness Modulus (ITSM) configuration, with Linear Variable Differential Transformers (LVDTs) to measure the horizontal deformation at the mid-span of the circumference of the specimens. During testing, a vertical load is applied to the specimen by loading strips, which causes a relatively uniform tensile stress in the horizontal direction perpendicular to the plane of loading [8, 9]. During normal traffic conditions, asphalt acts elastically and its ITSM directly relates to its bending resistance and the load spreading ability [10]. Following the BS-EN-12697-26:2018 test method [11], Annex C, the following parameters were used for determination of stiffness modulus of the mixture cores: (1) Target rise time = 124 ± 4 ms; (2) Mean horizontal deformation = 5 ± 2 µm; (3) Poisson's ratio = 0.35; (4) Diameter = 100mm; (5) Thickness = 40mm; Temperatures = 0˚C – 50°C at 10°C increments. The samples were conditioned at each temperature for at least 4 hours. A total of 6 samples per mixture type were tested for ITSM. Testing began at the lowest temperature and proceeded to the highest. The stiffness modulus was automatically computed by the NAT using Eq. 1 [11].

$$S_m = \frac{F(v + 0.27)}{zh} \qquad \text{Eq. 1}$$

Where: S_m is the indirect tensile stiffness modulus (MPa); F is the peak value of the applied vertical load in Newtons (N); z is the amplitude of the horizontal deformation obtained during the load cycle in millimetres (mm); h is the mean thickness of the test specimen in millimetres (mm); v is the Poisson's ratio, set to 0.35 for bituminous materials.

3 Test Results and Discussion

From the gain in stiffness from the control mixture (i.e., 0%HL) to the mixtures with maximum HL content (i.e., 3% HL) shown in Table 1, it is observed that the stiffening effect was more prominent at intermediate temperatures (i.e., 20°C and 30°C) in contrast to the lower- and upper-temperature spectrum. This clearly represents experimental evidence of the temperature-dependency of the stiffening effect that was previously theorised in literature [1, 3]. This observation is presented in *italics* in the last column of Table 1, and it refers to the increase or gain of average stiffness modulus of the mixtures between 0%HL and 3%HL. This finding is consistent with previous studies by [1], and it is explained in terms of the physical interaction of HL with the bitumen to increase the mastic stiffness at intermediate temperatures, whereas this effect is reduced with higher and lower testing temperatures. It is also observed that the lower temperatures exhibited the highest variability in terms of the standard deviation values and COV.

Table 1. Comparison of the stiffness moduli at six testing temperatures and basic statistics.

Mixture Type	Test Temperature (C)	Average Stiffness (MPa)	Standard Deviation	COV (%)	Gain of Stiffness (Control to 3% HL) (MPa)	Percent gain of stiffness (Control to 3% HL) (%)
0%	0 °C	16,385	1,395	9	3,138	19.15
1%		18,101	1,067	6		
2%		19,048	940	5		
3%		19,523	789	4		
0%	10 °C	9,263	464	5	2,263	24.43
1%		11,236	351	3		
2%		11,396	140	1		
3%		11,526	327	3		
0%	20 °C	3,478	75	2	1,119	*32.16*
1%		4,366	88	2		
2%		4,562	93	2		
3%		4,597	70	2		
0%	30 °C	1,060	83	8	395	*37.29*
1%		1,295	44	3		
2%		1,477	37	3		
3%		1,455	45	3		
0%	40 °C	407	25	6	100	24.05
1%		450	27	6		
2%		513	36	7		
3%		507	48	9		
0%	50 °C	219	1	1	41	18.91
1%		194	12	6		
2%		260	9	3		
3%		261	11	4		

As shown in Fig. 1 the correlation of stiffness modulus and HL content for each testing temperature considered exhibit a clear reduction of the stiffness rate of increase (slope of the linear fitting) as the temperature increases from 0°C to 50°C. Furthermore, the comparison of temperature and HL content shows that the average stiffness approaches very low values as the testing temperature goes above 30°C. Interestingly, as shown in Fig. 1, the lowest testing temperature (0°C) had the highest coefficient of determination, ($R^2 = 0.9324$), which substantiates a strong linear correlation between these variables. Notwithstanding, the strength of the correlation was lower for other temperatures due to the thermo rheological behaviour of bitumen and the typical variability associated to mechanical testing of bituminous materials. Hartman et al. [10] stated that at higher temperatures the non-linear and viscoelastic material behaviour is more pronounced which would appear to be in agreement with the results.

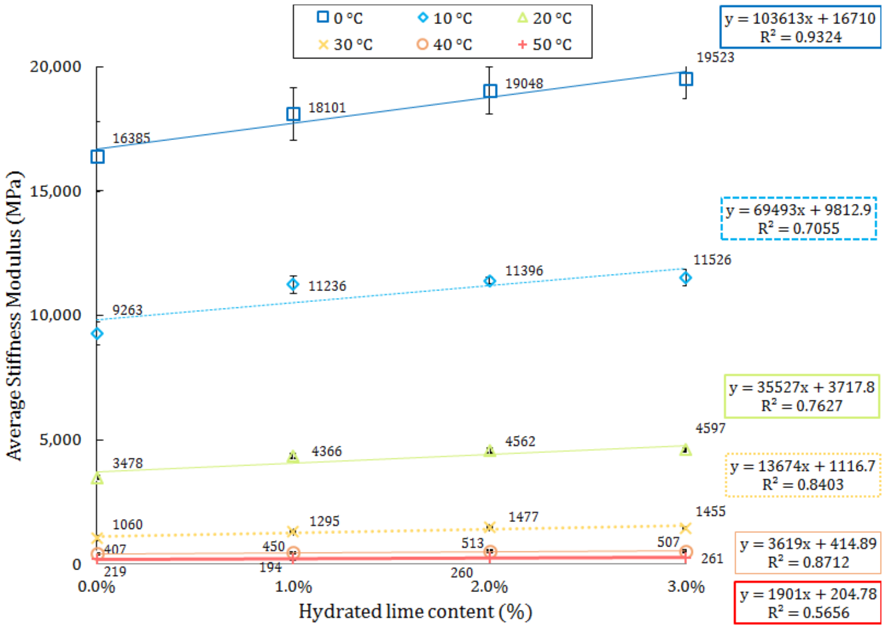

Fig. 1. Comparison of the effect of HL on the stiffening effect of bituminous mixtures at various testing temperatures (0°C to 50°C, at 10°C increments).

4 Conclusions

This paper assessed the temperature-dependency of the stiffening effect induced by hydrated lime (HL) on Stone Mastic Asphalt (SMA) mixtures. Based on the results and data analysis, the following conclusions are drawn: (*i*) The temperature-dependency of the stiffening effect induced by HL was clearly identified with experimental data; (*ii*) Except for the 50°C testing temperature ($R^2 = 0.56$), both the HL content and the average stiffness of the core specimens exhibited a linear correlation as substantiated by high correlation coefficients ($R^2 > 0.7$); (*iii*) The increase in testing temperature reduced the impact of the stiffening effect induced by HL on the manufactured mixtures; (i*v*) At high temperatures (above 40°C), the addition of hydrated lime to the SMA mixtures and the average stiffness follow a more non-linear correlation; and (*v*) the change in stiffness of the mixtures with incorporated HL with respect to the control mixtures (0% HL) indicated that the partial replacement of natural filler (i.e., limestone filler) leads to stiffer mixtures which are expected to have less susceptibility to permanent deformation, thereby substantiating the ability of HL to act as an *active filler* in the SMA mixtures produced.

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