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Estimation of low-temperature performance of recycled asphalt mixtures through relaxation modulus analysis

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A B S T R A C T

In cold climates, pavements undergo extreme thermal conditions which cause premature cracking and failure. The inclusion of Reclaimed Asphalt Pavement (RAP) could worsen this tendency due to the reclaimed bitumen stiffening effects. However, nowadays strict economic and environmental sustainability requirements strongly encourage the use of high RAP content in asphalt mixes.

In this context, this paper discusses the low temperature performance of mixtures designed with 40% RAP according to the Bailey method. Different bitumen contents and polymer modification levels were employed. A mixture with 25% of unfractioned RAP was employed as the reference mixture.

Laboratory tests were performed through Asphalt Thermal Cracking Analyzer (ATCA) by applying thermal loadings on restrained and unrestrained asphalt beams. Based on experimental data the relaxation modulus was evaluated to rank the materials. Its accurate determination is fundamental for designing long lasting pavements with proper performance at low temperature. The analysis was performed through a new analytical methodology for obtaining the relaxation modulus master curve by measuring thermally induced stress and strain. The solution, based on Boltzmann's equation and pseudo-variables concepts, accounts for time and temperature dependency of bituminous materials, avoiding complex integral transformations. The proposed solution successfully integrates the current ATCA analysis providing reliable estimations of relaxation properties fundamental in modelling of pavement behavior. Mixtures containing 40% RAP demonstrated enhanced relaxation capabilities at low temperature showing significant improved behaviours than the reference mixture. Although high amount of reclaimed material, proper selection of RAP and type and quantity of virgin bitumen can improve low temperature performance.

1. Introduction

Low-temperature cracking is one of the most common failure modes for flexible pavements (Dave et al., 2016; Geng et al., 2010; Liu et al., 2015; Özgan and Serin, 2013; Pirmohammad and Ayatollahi, 2015; Zhong and Geng, 2009), especially in cold climate regions where the daily temperature drop can be extremely rapid, the lowest temperature experienced very low, and the cold season very long. As a consequence, continuous maintenance and rehabilitation activities are required to keep acceptable in service conditions, resulting in high direct and indirect costs. Thermal cracking is believed to become even more significant when a certain amount of Reclaimed Asphalt Pavement (RAP) is included in Hot Mix Asphalt (HMA). Thermal cracking susceptibility could be emphasized due to the expected increase in stiffness caused by the aged binder contained in RAP aggregates that could also induce higher brittleness and, consequently, lower thermal cracking resistance (Hill et al., 2013; Mensching et al., 2014). On the other hand, nowadays the use of RAP for the production of new mixtures is strongly encouraged due to both economic and environmental reasons (Colbert and You, 2012; Mangiafico et al., 2013; West and Marasteanu, 2013). Agencies and contractors are in favour of using larger amounts of RAP in asphalt mixes but at the same time require that the in service performance of recycled pavements fulfil all the requirements specified by technical specifications for traditional mixtures. Therefore, recycled HMAs must be appropriately designed both in terms of aggregate gradation and bitumen content and type. The design should cover the parameters related to the main distresses that a flexible pavement can suffer during its service life in order to identify the best compromise or the most proper solution for particular climate and traffic conditions.

In this context, a fundamental indicator to investigate the low-temperature performance of bituminous mixtures is the relaxation modulus. It represents the capability of a mixture to dissipate the stress applied by thermal loads. In particular, when flexible pavements are

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subjected to significant temperature changes, continuous variations in stresses take place due to restraining of contractions and expansions in bituminous layers. During the cooling phase, the difference in temperature between the surface and the deeper layers as well as the bond at the interface between layers cause a restrained contraction that can result in the formation of top-down cracks when the ultimate tensile strength is exceeded by the thermally induced stress (Brown et al., 2009; Dave et al., 2016; Muna and Lee, 2010; Pirmohammad and Kiani, 2015).

Bearing all this in mind, it is easy to understand that the relaxation capability of a mixture plays a fundamental role since the higher the relaxation potential, the lower the potential to reaching the failure point (i.e. crack formation). Mixtures characterized by faster decay of relaxation modulus are less prone to cracking at low temperature and can be more suitable for use in cold climate regions. However, the appropriate determination of the relaxation modulus is not simple. Over the last years, few attempts in this direction (Alavi et al., 2013; Dave et al., 2016; Hesp, 2004; Hill et al., 2013; Marasteanu et al., 2012) were not able to solve and simplify the overall complexity of the problem mainly due to the inability to take concurrently into account the time and temperature dependency of bituminous materials. No adequate testing protocols and equipment, nor proper analysis methods were available to calculate the relaxation modulus. These challenges were solved by recent studies that developed a specific data analysis method able to simply calculate the relaxation modulus using the data recorded through the new Asphalt Thermal Cracking Analyzer (ATCA) equipment (Canestrari et al., 2015).

The ATCA device (Bahia et al., 2012), proposed as provisional AASTHO test method, allows the concurrent measurements of thermally induced stress and strain on restrained and unrestrained mixtures specimens, respectively.

In this paper, based on previous studies (Canestrari et al., 2015), data are collected through an analytical procedure able to take into account both the time and temperature dependency of asphalt mixtures behavior, while avoiding sophisticated inter-conversions or complex numerical approximation. The new analysis methodology adopted, based on the Boltzmann's equation and the pseudo-variables concept, leads to the determination of the relaxation modulus master curve for the studied mixtures, hence allowing the performance comparison of different materials. Based on ATCA device measurements, and using the abovementioned mathematical approach, this paper studies the low temperature performance of mixtures designed including 40% of RAP. The analysis is performed by comparing the relaxation modulus master curves and by relating the relaxation capability to other fundamental parameters that describe the mixture behavior. Moreover, the 40% RAP mixtures were compared with a mixture including 25% of RAP, used as a reference since it is the mixture currently employed in the Italian motorway system and is commonly believed to provide good performance both at high and low temperature.

1.1. Objectives

The main objective of this research work is to verify that increasing the RAP content up to 40% in pavement layers does not compromise low-temperature mixture performance in terms of cracking resistance. The relaxation modulus was the main parameter adopted to evaluate the cracking resistance performance. The relaxation capability allows the effects of polymer modification and bitumen amount to be detected, and hence the determination of the most suitable combination in terms of type and content of bitumen and aggregate gradation when recycled mixtures are used in cold climates.

2. Experimental program

2.1. Materials

The experimental investigation involved five hot recycled asphalt mixtures designed with a Nominal Maximum Aggregate Size (NMAS) of 20 mm to be used for binder layers. Four mixtures were prepared with 40% of RAP by aggregate weight. The RAP included was obtained by milling of old bituminous base and binder layers prepared with Styrene-Butadiene-Styrene (SBS) modified bitumen (coded as H, high modified bitumen with 3.8% of SBS polymer by bitumen weight). The RAP was processed (crushed and screened) and sieved into two fractions (i.e. 8/16 mm and 0/8 mm). This process was adopted in order to avoid the presence of foreign matter and too large clumps and to achieve a better control of the aggregate gradation by reducing the variability often related to RAP sources. The Bailey Method, adjusted to be suitable for the common European mix design practices (Graziani et al., 2012; Vavrik et al., 2002), was used to optimize the aggregate grading curve of the 40% RAP mixtures according to the grading envelope specified by the technical specification for binder layers.

In order to identify the best combination in terms of bitumen, the 40% RAP mixtures were prepared using two total bitumen contents (5.0% and 5.2% by aggregate weight). It is worth noting that the total bitumen content accounts for the virgin bitumen added to the mixture and all the RAP bitumen. Different amounts of total bitumen content were investigated since RAP bitumen partially reactivates in an unknown percentage comprised between the black aggregate condition and the full reactivation (Stimilli et al., 2015a). Additionally, each total bitumen content was prepared using two virgin bitumen types (low modified bitumen “L” and high modified bitumen “H”), both modified with radial SBS polymer equal to 1.8% and 3.8% by bitumen weight, respectively (Stimilli et al., 2014). The L and H bitumen had different performance grade (PG) as shown in Table 1. The effect of bitumen grade was investigated in order to evaluate whether the use of low modified bitumens can help to compensate the increase in stiffness resulting from high amount of RAP, which is a critical aspect for the development of good performance of mixtures at low-temperature.

Table 1
Basic characteristics of the virgin bitumens.

Binder characteristics	Aging	Standard	Unit	Virgin bitumen L	Virgin bitumen H
SBS polymer content by weight	–	—	%	1.8	3.8
Penetration [25 °C; 100 g; 5 s]	Virgin	ASTM D5	0.1 mm	60	54
	RTFOT			61	27
Ring and ball softening point	Virgin	ASTM D36	°C	66	71
	RTFOT			73	77
Dynamic viscosity @ 135 °C	Virgin	ASTM D4402	Pa·s	1.15	1.24
Mass loss after RTFOT	RTFOT	ASTM D2872	%	0.08	0.05
$G^*/\sin\delta$ @ 10 rad/s, 64 °C	Virgin	ASTM D7175	kPa	2.08	2.55
	RTFOT			8.32	7.76
$G^*\cdot\sin\delta$ @ 10 rad/s, 25 °C	PAV	ASTM D7175	kPa	2283	1295.50
Creep stiffness @ −12 °C	PAV	ASTM D6648	kPa	289,929	40,479
Creep stiffness @ −18 °C	PAV	ASTM D6648	kPa	334,420	65,190
PG		AASHTO M 320		64–22	64–28