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Investigating physical and rheological properties of foamed bitumen

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HIGHLIGHTS

- The addition of a foaming additive marginally decreased viscosity of neat bitumens.
- Foaming additive affected bitumens' rheological properties.
- Bitumens with the same penetration grade provided very different foam-abilities.
- Thermal analysis through differential scanning calorimetry revealed good correlation with bitumens' foaming properties.

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ABSTRACT

Foamed asphalt mixes are gaining ground as effective alternatives to asphalt base and sub-base standard layers in Europe and in other countries worldwide. As a significant amount of research is being conducted to advance sustainable practices for road pavements, foaming asphalt mixes have become a valid option to common asphalt paving technologies. Several advantages and the environmental benefits of foamed asphalt mixes have been debated and assessed.

The present study aimed to evaluate: (1) the foaming characteristics of several bitumens sourced from different refineries with the same classification grade; (2) the physical, rheological, and chemical properties of bitumens before and after foaming; and (3) the effectiveness of a foaming additive in the enhancement of final product performance.

Results showed that the same penetration-grade bitumen can provide very different results in terms of foaming properties (expansion ratio and half-life) depending on its chemical composition (differential scanning calorimetry and optical microscope analysis). The experimental program also assessed how the foaming process affected the physical and rheological behavior of bitumens (penetration, Ring and Ball test, dynamic viscosity, complex modulus, and phase angle).

1. Introduction

Keeping roads in good condition requires regular maintenance activities. This maintenance, given the large extent of the road networks, consumes a massive amount of non-renewable resources, mainly virgin aggregates. In addition, standard maintenance and rehabilitation activities create delays for users, traffic capacity deficiencies, safety issues for construction site workers and drivers, and demand a large amount of material handling and equipment. The economic crisis, increased costs of materials, and a strong desire to maintain a safe, efficient, and sustainable roadway system have fueled a resurgence of recycling existing pavement as a primary option.

It is acknowledged that limiting the disposal of old pavement materials, therefore minimizing the use and transport of virgin aggregates, as well as reducing landfilling, lowers environmental impact. These benefits, combined with the lower temperatures used in asphalt recycling, might lead to the belief that recycling always represents an eco-effective strategy. However, producing asphalt mixes at lower temperatures represents a successful alternative only if the final pavement is then able to compete, in terms of durability for instance, with standard hot-mixes. Also, the environmental effects of foaming agents or additives, if used, have to be as low as possible to achieve good results in the Life Cycle Assessment (LCA) of the product.

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Currently, different techniques are used to recycle existing pavements. One of the most adopted is based on foamed asphalt mixes. However, despite significant advancements in the last decade, the adoption of foamed asphalt still relies substantially on empirical trials and lacks universally accepted mix-design procedures. Foamed asphalt mixes are mainly adopted by European countries as a cost-effective replacement for base and sub-base layers; full-depth recycling and cold-in-place methodologies are generally considered hard to implement on upper surface layers due to high inhomogeneity of the existing paved materials (e.g., different age of the sections to be recycled, dimension and shape of aggregates, binder content, oxidation of the binder, etc.) even for relatively small areas. Moreover, it is generally agreed that cold-recycled mixes end up being a cost-effective method but with inferior long-term performance with respect to hot-mixes.

The mechanical performance and durability of foamed asphalt mixes rely on the physical and rheological properties of foamed bitumen, which should be in turn assessed. The present study investigated bitumen properties before and after being foamed. Besides traditional testing (penetration and Ring and Ball [R&B]) more advanced tests were conducted on foamed bitumen using the following equipment: Brookfield Rotational Viscometer, Dynamic Shear Rheometer (DSR), differential scanning calorimetry (DSC), and optical microscope imaging.

1.1. Background

Foamed bitumen is a mixture of hot bitumen, water, and air; sometimes a foaming additive is added to improve the quality and the stability of the foam. Spraying simultaneously hot bitumen (normally between 150 and 180 °C) and water (ambient temperature) causes the mix to expand several times its original volume generating a fine mist or foam.

The production of effective foamed bitumen mixes for pavement recycling applications can only be achieved when the bitumen adopted shows suitable foaming characteristics. Efficient methodologies for defining bitumen foaming properties are consequently of critical importance if efficient roadways are to be constructed or recycled. To date, foam is principally measured according to two main parameters: the expansion ratio (ER), which measures the increase of bitumen in volume after being sprayed, and the half-life (H-L), which evaluates the durability and the stability of the foamed-state before collapsing [1,2]. However, the adoption of ER and H-L has been criticized for several reasons [3–6]:

1. these parameters do not measure a physical material property, and any correlation between the test results and performance has to be ascertained through experience.
2. These parameters do not permit a full understanding of the mechanism of foamed asphalt and how it forms and decays; consequently, it is not understood why certain bitumens make good foam while others do not, even if very similar; and
3. the ER and H-L tests are operator-dependent and therefore highly variable.

Theoretically, the viscosity of bitumen is acknowledged as one of the main variables influencing the foaming properties; softer bitumen with a low viscosity produce higher expansion ratios and longer H-Ls with respect to harder, high-viscosity bitumens, whilst the use of high-viscosity bitumen is assumed to achieve superior coating of the aggregates [7]. However, the effect of viscosity on foaming potential is still not entirely clear.

Limited literature also exists on the effects of foaming processes on bitumen chemistry and, vice versa, how bitumen chemistry affects the potential foaming properties. Studies by Barinov [8] showed that increasing the asphaltene fractions of bitumen increased the ER and H-L; asphaltenes can indeed act as surfactants that delay the foam from collapsing.

Lesueur et al. [3], realized that bitumen composition did not greatly influence the foaming properties. Namutebi et al. [9] revealed that the presence of waxes within the binder enhances the foam characteristics. Jenkins [10] reported as a drawback that some bitumen may a priori contain anti-foam additives, incorporated during refining processes to precisely avoid the creation of foam during manufacturing and hauling.

In addition, investigating the foaming properties of bitumen before and after the foam has been created entails several complications. As said, foam remains stable for a relatively short amount of time (seconds) and then collapses; collecting samples in a foam-condition state and suddenly performing tests is therefore hard to achieve (i.e., if a standard penetration test is conducted at 25 °C after the sample has been cured in a constant temperature water bath for at least one and a half hours [11], the original foam will partially disappear in that time). If left at ambient temperature for a long time, foamed bitumen might lose part of its air content (bubbles). Sunarjono [12] tried to preserve the foam-condition state by exposing samples of foamed bitumen to very low temperatures in a refrigerator just after spraying in order to conduct testing later; Kutay et al. [13] soaked foamed bitumen samples in liquid nitrogen to instantly freeze the foam and conduct tests later.

The present study investigated the foaming properties of bitumens, correlating standard foam-experience results (ER_M and H-L) with rheological and chemical properties of the material before and after being foamed.

1.2. Objective

The objective of this paper was to evaluate the effect of foaming processes on physical, rheological, and chemical properties of three bitumens having the same penetration grade but sourced from different refineries. The effectiveness of a foaming additive was also investigated.

2. Materials and experimental program

2.1. Materials

Three types of bitumens were sourced from three different refineries in the northern part of Italy and examined further. For the purpose of the present research, they were named Bitumen A (Bit A), Bitumen B (Bit B), and Bitumen C (Bit C). Although coming from different refineries, they were classified as having the same penetration grade, 70–100 dmm [14].

A foaming additive was also added to Bit B and Bit C for analyzing its influence on bitumen properties before and after the foaming process. Bit B and Bit C blended with the foaming additive (ADD) are denoted as Bit B + ADD and Bit C + ADD. The specific density of the foam agent was 0.9 g/cm^3; the flash point was 170 °C; its chemical composition was based on oleic acid diethanolamine. The recommended dosage by the supplier ranged between 0.4% and 0.6% by weight of bitumen; in particular, the 0.6% concentration was used in the present study. The standard physical properties of the bitumens used are provided in Table 1.

It can be observed that (1) even if assessed as having the same penetration grade (70–100 dmm), Bitumen A exhibited a higher penetration, probably due to unidentified additives adopted for stabilizing bitumen during refining and hauling; (2) the foaming additive (Bitumens B + ADD and C + ADD) provided a consistent softening of neat Bitumen B and C, resulting in higher penetration and lower softening temperature. Table 1 also shows penetration indexes (PI) for unfoamed bitumens ranging between −0.68 and −1.91. Good paving bitumens usually provide a PI between −1 and +1, while temperature-susceptible bitumens present a PI lower than −2 [14]. Bitumen A was, therefore, the most temperature susceptible among bitumens tested.

The experimental plan included four main sections:

(a) evaluation of physical, rheological, and chemical properties of three types of virgin bitumens (a foaming additive was then added to two of them);
(b) assessment of the foaming properties using the Wirtgen Laboratory-Scale foamed bitumen machine (WLB-10S);
(c) characterization of physical and rheological properties of post-foam bitumens; and