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An advanced methodology for the mix design optimization of hot mix asphalt

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ABSTRACT

The bitumen quantity to add to asphalt mixtures depends on the surfaces of aggregates and filler to be coated. The formulas currently available in the literature have limitations such as considering all the fillers with the same specific surface or the aggregates with spherical or cubical shapes. This paper aims to define an analytical approach for the determination of the optimal dosage of bitumen in HMA proposing new methodologies to go a step further in the resolution of the above mentioned approximations. Indeed, new surface area factors were calculated to determine the aggregates surface considering their real shapes and volumes. Afterwards, the authors proposed a detailed characterization of two types of fillers and the *critical filler concentration*, introduced by Faheem and Bahia, was used to calculate the minimum amount of bitumen for maintaining the mastic in a diluted state and filling the voids in the mixtures. Finally, a verification of the formula developed was carried out with specific laboratory tests. These results allow the challenge of revising the method of calculating the specific surface of the aggregates and filler to be addressed with the final goal to include them in a new mix design optimization for HMA.

1. Introduction

Optimal dosage of bitumen in HMA has always been a challenge because of the complexity of estimating the optimal average film thickness around the aggregates and satisfying at the same time the Voids in the Mineral Aggregates (VMA) requirements [1]. Thus, for an optimization of the mix design of HMA, the definition of the optimal bitumen film thickness is fundamental for achieving a high performance level of asphalt mixtures. For instance, too thin bitumen films are more easily penetrated by water resulting in moisture damage [2]. Moreover, a poor coverage can cause a lack of bonding among aggregate particles in the mixture. On the other hand too thick film might result in an excess of lubrication increasing risk of rutting or flushing. Campen et al. [3] proposed the optimal “average film thickness” ranging from 6 to 8 μm, others suggest 9–10 μm for minimizing aging [4] or between 9.5 and 10.5 μm for minimizing the effect of moisture [2]. Moreover, the determination of the optimal thickness requires further analysis if the bituminous mixture contains RAP [5–7]. The numerous efforts in this research domain over the last years [8–10] demonstrate that the achievement of adequate bitumen film thickness around the aggregates and filler is fundamental to ensure the durability of asphalt mixture.

2. State of the art and objective

Several proposals have been made for calculating the bitumen thickness around the mineral aggregates for mix design purpose [11–15]. All calculations are based on the aggregate specific surface area (SSA), as principal parameter for the estimation of the film thickness required for the optimal coverage and bonding of the aggregates.

For instance, Hveem [16] estimated the surface area of the aggregates SSA (m^2/kg) by applying the following equation:

$$SSA = \sum_{i}^{n} SF_i \cdot P_i \tag{1}$$

where SF_i are the surface area factor (m^2/kg) that corresponds to the i-sieve, P_i is the percentage passing by weight the i-sieve and n is the number of sieves. The surface area factors proposed by Hveem are the ones currently used by the Asphalt Institute Manual series 2 [17]. The

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method assumes that the particles are spheres with smooth sides and have the same density [18].

Duriez and Arrambide [19] proposed the following equation:

$$SSA = 0.25g + 2.30S + 12s + 135f \tag{2}$$

where:

- g percentage of gravel by weight (grains above 5 mm sieve)
- S percentage of coarse sand by weight (grains between 0.315 and 5 mm sieves)
- s percentage of fine sand by weight (grains between 0.080 and 0.315 sieves)
- f percentage of filler by weight (grains below 80 μm).

The origin of the coefficients used in Eq. (2) was found considering the aggregates as cubes [20]. For the fines the coefficient (135 m^2/kg) was defined as average for different fillers. The result is that the above mentioned methods use a constant surface area for the filler particles, independently of their mineralogy and gradation. Moreover, they are all based on the approximation of considering the aggregates as spheres or cubes and of the same density.

More advanced methods that distinguish among several types of fillers were proposed later by Craus & Ishai and Chapuis & Légaré [21–22]. Craus and Ishai, for example, proposed different surface area factors and Chapuis and Legare introduced the Eq. (3) for the SSA calculation.

$$SSA = \left(\frac{6}{\rho_s}\right) \cdot \sum[(P_{No\,D} - P_{No\,d})/d] \tag{3}$$

- ρ_s density of the sphere or cube [kg/m^3]
- $(P_{NoD} - P_{Nod})$ percentage by weight smaller than sieve size D and larger than next sieve size d [%]
- d diameter of the sphere or edge length of the cube [m].

The same equation was extended to the particles smaller than 80 μm considering their gradation and different mineralogy. Chapuis and Légaré sieved the mineral fillers and they used Eq. (3) to compute the specific surface area. Then they compared the estimated results with the measured specific surface using the Blaine air permeability apparatus (ASTM C204). Differentiating the contribution of different types of fines depending on their particles distribution allowed increasing the accuracy in the calculation of the surface compared to the singular coefficient used in Eq. (2). However, the problem of the approximation of the shape of the aggregates (fines and coarse) assumed as spheres or cubes was not solved. Moreover, the values that they have obtained were much greater than the Hveem or Craus and Ishai surface area factors and not directly usable for the determination of the calculation of the bitumen film thickness. The reason of this difference will be widely discussed later in the paper.

The objective of this paper is to propose an advanced methodology and tools for calculating the optimal bitumen quantity of HMA mixtures with specific focus on the determination of the SSA to be coated.

3. Materials

Aggregates from Choex-Massongex (Switzerland), and two types of fillers (limestone and hydrated lime) were used for the study. The characteristics of the aggregates and fillers are summarized in Table 1.

4. Methodology

Several approaches were applied to study the contributions of aggregates (d > 0.063 mm) and filler (d < 0.063 mm). This resulted in a new calculation of the binder dosage once the optimal average bitumen thickness around the aggregates was selected from the literature equal to 10 μm [4] for all the aggregates bigger than 0.063 mm. The starting point, established by the authors, of the calculation carried out in the present study is represented by Eq. (4):

$$V_{bit-tot} = \bar{t}_{opt-agg} \cdot SSA_{agg} + V_{bit-filler} \tag{4}$$

where

- $V_{bit-tot}$ total volume of virgin bitumen to add to the mixture [m^3/kg]
- $\bar{t}_{opt-agg}$ optimal average thickness of virgin bitumen around all the aggregates (d ≥ 0.063 mm) [m]
- SSA_{agg} surface area of aggregates (particles with d ≥ 0.063 mm) [m^2/kg]
- $V_{bit-filler}$ volume of bitumen required to coat the filler (particles with d < 0.063 mm) [m^3/kg].

The separation of the contributions of aggregates and filler in Eq. (4) is based on the different role that the two materials play in the mixtures. Indeed, the aggregates represent a lytic skeleton to be covered. The filler with the bitumen represent a diluted mastic phase that fills the interstitial voids created by the blend of the coarse aggregates [23]. Therefore the filler can be considered as suspended in the bitumen. Hence the amount of bitumen absorbed by the finest part is higher than the bitumen absorbed by the aggregates. Thus, two different effects were considered to calculate the filler and the aggregate contributions.

In order to obtain the optimal dosage of bitumen, the parameters in Eq. (4) have to be defined. Therefore, the paper focuses on:

1. Determining reviewed surface area factors (α_i) for aggregates with d > 0.063 mm
2. Accurate measuring specific surface of filler and the volume of bitumen absorbed by the fine particles.

For achieving these objectives, several steps were carried out:

- The surface area factors (Hveem and Craus & Ishai) were revised based on the real shapes of aggregates by a laser scanning. The images obtained were analyzed with Meshlab software version 1.3.3;
- Two types of fines particles commonly used in road construction (limestone and hydrated lime) were characterized, carrying out several steps: Rigden voids test, particles size distribution (PSD) with laser diffraction, Brunauer, Emmett and Teller (BET) method and the calculation of the agglomeration factor. To visualize the shape and agglomeration of the particles Environmental Scanning Electron Microscope (ESEM) images were captured. Finally the concept of *critical filler concentration* [24–25] was used to determine the bitumen quantity necessary for maintaining the mastic (bitumen + filler) in a diluted state.

The theoretical calculations were subsequently verified carrying out laboratory tests. Hot mix asphalt concretes with different binder contents (4.5; 5; 5.5 and 6%) were prepared and compacted using the Marshall hammer and gyratory compactor. Marshall tests and Indirect Tensile Strength Test (ITST) were performed to verify that the proposed methodology estimates reliable values in comparison with the measurements.

4.1. Revision of the surface area factors

Spheres or cubes were always used as approximation for estimating the surface area of mineral aggregates [26]. In order to overcome this