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Prediction of water evaporation and stability of cold asphalt mixtures containing different types of cement

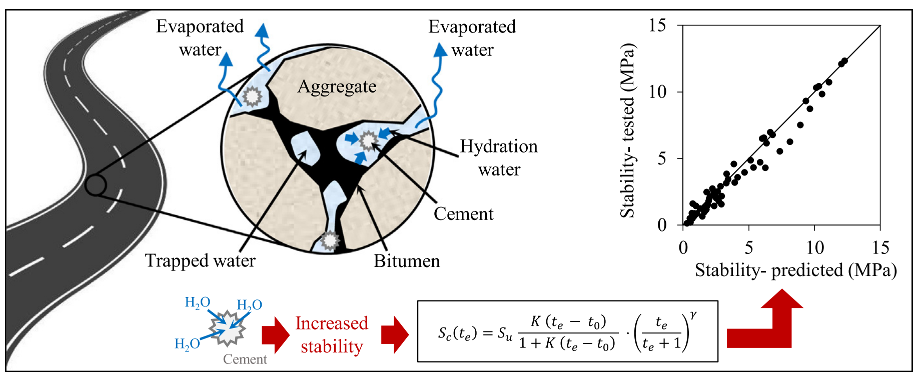
Tahseen Saadoon, Breixo Gómez-Meijide *, Alvaro Garcia

Nottingham Transportation Engineering Centre [NTEC], Department of Civil Engineering, University of Nottingham, Nottingham NG7 2RD, UK

HIGHLIGHTS

- Studied the effect of cement on water evaporation dynamics in CAM.
- Tested CAM with ordinary Portland cement and two types of rapid hardening cement.
- Tested with dynamic evaporation, hydraulic conductivity and Marshall test.
- Cement increases the stability of CAM but does not significantly shorten drying time.
- A predictive model for the contribution of cement to total stability was developed.

GRAPHICAL ABSTRACT



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ABSTRACT

The mechanical performance of cold asphalt mixtures (CAM) can be improved by using cement additions, but it is unclear how this affects the dynamics of water evaporation during drying. This paper investigates CAM samples with different contents and types of cement (ordinary Portland, calcium aluminate and calcium sulfoaluminate), tested by dynamic evaporation, hydraulic conductivity and Marshall test. The results show that cement does not significantly shorten the drying process, while bitumen emulsion delays cement hydration. Finally, a new predictive model was obtained to estimate the contribution of cement hydration products to the total stability of CAM.

1. Introduction

Asphalt, essentially a mixture of aggregate and bituminous binder, is one of the most widely used construction materials in civil engineering. Depending on its temperature during mixing, it can be classified into four main types: hot, warm, half-warm, and cold asphalt mix [1]. As they do not need any heating, cold asphalt mixes (CAM) compared to the other types of construction materials used in pavements (e.g. hot mix asphalt, HMA) have positive impacts in terms of its environmental, economic, energy saving, and health and safety performance. A distinguishing feature of CAM is that aggregates are mixed with asphalt emulsion, which contains water. Moreover, extra water is usually added to obtain optimum compaction.

The curing process of CAM involves the evaporation of water and volatiles and the beginning of breaking of the emulsion [2], when the particles of bitumen start attaching to each other forming a continuous film, which coats the aggregates. The evaporation of this water can be prolonged, particularly in colder climates [3],

* Corresponding author.
E-mail address: breixo.gomez.meijide@nottingham.ac.uk (B. Gómez-Meijide).

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which reduces the mechanical performance of CAM, especially during the initial curing stages [4]. Consequently its use has been generally restricted to the construction of non-structural pavement layers in low-traffic roads [5]. Therefore, curing is a fundamentally important stage in the performance of CAM.

Over recent decades, many studies have attempted to improve the mechanical performance of CAM during the early curing stages by adding cement [6,7], which accelerates the emulsion breaking by consuming the water via hydration, and changing the chemical stability of the bitumen emulsion by increasing alkalinity [8,9]. Moreover, cement works as secondary binder after hydration, improving the stability of the material. The process can also be accelerated by using rapid hardening cements, such as calcium aluminate cements (CAC) and calcium sulphate (or calcium sulphoaluminate) cements (CSA) [6,10]. In comparison to ordinary Portland cement (OPC), these types of cement (especially CSA) improve performance, especially during the first days, as they have a faster hydration process, and consume more water during this.

Although these types of cement have been widely investigated as binders in concrete, their effect on the water dynamics of CAM have not been studied.

2. Theoretical considerations and objectives

2.1. Prediction model for CAM stability

Predicting the mechanical properties of CAM with different types and quantities of cement has great importance to accurately design the mix and predict its performance under traffic loads at any stage of the curing/drying process. For this reason, the following semi-empirical model has been developed [11] by considering that the total stability of the mix is the sum of the stability provided by the mineral skeleton (aggregates), plus the broken bituminous emulsion and the products of cement hydration, acting on the three sources independently, as follows:

$$S(t) = \frac{h_d(t)}{H}(S_d - S_w + \alpha) + S_w + S_c(t) \tag{1}$$

where $h_d(t)$ is the thickness of the dry layer at a given time (t); H is the total thickness of the material; S_d is the strength of the granular material under dry conditions; S_w is the strength of the granular material under saturated conditions; α is a relationship constant depending on characteristics, such as binder-aggregate affinity and binder content; and $S_c(t)$ is the strength provided by the products of cement hydration at a given time (t).

The following equation was also proposed [11], which allows the prediction of the thickness of the dry layer (h_d) as a function of the pore size distribution (n), which changes with time in CAM:

$$h_d = \frac{\left[\frac{1}{n_2}\ln\left(\frac{n-n_0}{n_1}\right)\right]^{k_1}}{k_2 n_2 + \ln\left(\frac{n-n_0}{n_1}\right)} \cdot k_0 n_2 \tag{2}$$

where n_0, n_1, n_2, k_0, k_1 and k_2 are different material constants related to binder content, air void characteristics (such as tortuosity and pore interconnectivity), and environmental conditions during the drying process, such as temperature and humidity.

However, this model was only validated for granular materials and for CAM containing no cement. Hence, the evolution of n over the curing/drying process might be affected by the simultaneous reactions of water with cement and the precipitation of hydration products within the internal pore network. In addition, the contribution of cement to the total stability of CAM (term $S_c(t)$ in Eq. (1) has not been ascertained, thus the model is not yet suitable for application in CAM containing cement. Hence, the present investigation aims to develop and validate a predictive model for this term.

2.2. Water dynamics in CAM

As seen in Eq. (1), n is a fundamental parameter of CAM, related to the speed of water evaporation, which can be divided into three stages, first, transition and second [12,13]. During the first stage, the porous material is fully saturated, after which a semi-saturated layer (capillary fringe) is formed between the surface of the material and the saturated layer, indicating the beginning of the transition stage of evaporation. During the second stage, three different layers (dry, semi-saturated, and/or saturated layers) will be present in the porous material. The evaporation rate of water differs between the evaporation stages, as each stage has different mechanisms of evaporation [12,13]. As the evaporation rate decreases from the first to the second stage, in order to accelerate drying, it is important to prolong the first stage, which depends on capillarity [12,13], as much as possible.

The duration of the first stage of water evaporation in a porous material is strongly related to the maximum height of capillary action (L_C) that the internal pore network can provide [12,13]. Such upwards capillary action decreases when the pore size distribution (n) increases in the material [11] and it is also reduced by the opposite downwards action of gravity (L_G) and viscous forces (L_V), as described in Eq. (3).

$$L_C = L_G + L_V \tag{3}$$

When the material has very dense porous texture (e.g. clays), the effect of viscous forces is important. However, in other materials, such as CAM, the effect of viscous forces is practically negligible [14]. Consequently, for these materials, Eq. (3) is commonly simplified, as follows:

$$L_C \approx L_G \tag{4}$$

Based on the Van Genuchten expression for the water retention curve [15], Lehman et al. [14] proposed the following equation to calculate L_G:

$$L_G = \frac{1}{\alpha\,(n-1)}\left(\frac{2n-1}{n}\right)^{(2n-1)/n}\left(\frac{n-1}{n}\right)^{(1-n)/n} \tag{5}$$

where α (1/cm) is a parameter related to the inverse of the air entry suction that can be calculated as a function of the pore size distribution index (n) and parameter α_1, which was found in the literature review with different values, such as 0.134 [11] or 0.0087 [14] depending on the studied material:

$$\alpha = \alpha_1(n-1) \tag{6}$$

At the same time, it is known that the pore size distribution is related to the water-saturated hydraulic conductivity of porous material (Ks), making it possible to calculate n by Eq. (7), proposed in [14] and also used in [11]:

$$K_s = k_1 \cdot n^{k_2} \tag{7}$$

where k_1 and k_2 were 0.0077 and 7.35 respectively in [14], while they were 0.003 and 6.493 respectively in [11].

By applying Eqs. (5)–(7), L_C can be easily obtained by carrying out quick hydraulic conductivity tests, instead of by monitoring the material over the whole evaporation process. However, this was not yet proven for CAM containing cement, as the cement-water reaction and the precipitation of hydration products might change the hydraulic characteristics of the mix during the process. Hence, the present study investigates how the addition of cement affects the dynamics of water evaporation in CAM.