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Modeling the effect of environmental factors on evaporative water loss in asphalt emulsions for chip seal applications

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ABSTRACT

This paper proposes a methodology to determine the total amount of evaporative water loss of an emulsion before the aggregates are placed. An algorithm is presented that can be used by field inspectors and practitioners for the optimal timing of chip placement.

Evaporation of water from the emulsion was modeled as a two stage process. The first stage involves the emulsion losing water as it cools down from its application temperature until it is in a state of thermal equilibrium with the surrounding environment while the latter involves determining the amount of moisture loss due to the vapor pressure deficit in the ambient air and the turbulence in the surrounding environment. Finally, based on the observations from field construction programs, moisture loss thresholds were determined to calculate the optimal time to place the aggregates.

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1. Introduction

Asphalt products for road construction include asphalt cements, cutback asphalts and emulsified asphalts. The basic purpose of producing emulsified or cutback asphalt is to reduce the temperature at which it can be applied. From an environmental perspective, reduced temperatures and the omission of volatile fractions other than water are beneficial.

An asphalt emulsion is composed of three ingredients – asphalt cement, water, and an emulsifying agent. Asphalt emulsions that include an anionic surfactant base are categorized as anionic emulsions while those with a cationic surfactant base are classified as cationic emulsions. Anionic emulsifiers are commonly fatty acid derivatives that are saponified with sodium or potassium hydroxide. Similarly cationic emulsifiers are derived through salification of fatty amines. Special emulsion grades like "High Float" emulsions use higher quantities of emulsifiers, which gives a gel character to the residual binder after the emulsion breaks down.

The use of polymers to produce modified asphalt binders has created a whole new family of asphalt emulsions types. Letters P (polymer-modified) or L (Latex-modified) is suffixed to the name of base emulsion to designate emulsions that utilize polymer modified binders. Some agencies have an additional cationic sand-mix ing grade (CMS-2S) that contains more solvent than usual [1]. The suitability of an emulsion for a particular project is dependent on factors such as climate, type of job and type of aggregates, among many others.

Emulsion breaking signifies the phenomena in which a great majority of the droplets of the emulsion undergoes an irreversible process that results in the formation of a continuous macroscopic bituminous phase [2]. The emulsions are formulated to have a sufficient level of potential repulsion between the adjacent particles to prevent premature coagulation. The particles coalesce only if modification occurs, at least locally within the surfactant films [2]. This can be due to a variety of reasons including:

- A change in the hydrophilic and lipophilic balance of the emulsifier.
- A change in acidity or basicity (pH).
- An increase in the ionic force of the medium.
- Adsorption of the surfactant by the mineral aggregates.

Emulsion curing signifies the combination of phenomena which result in the removal of the water from the bituminous material, after the breaking phase is completed or is at least sufficiently initiated. This improves the mechanical properties of the product prepared with the emulsion [2]. The statement above therefore implies that the development of stiffness as well as its ability to hold the aggregates back will be governed by the rate of moisture removal from the system. Early placement of aggregates can lead

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to tire pickup by rollers while delayed placement of stones will require more compaction effort or in some cases improper embedment of stones which are dislodged within the first few weeks of opening to traffic [9].

Rejection of water from the aggregate surface is both a thermodynamic and kinetic effect. The thermodynamics relate to the energy differences between the emulsifier and the aggregate charge, the kinetic to the diffusion controlled loss of water through the coalescing binder [3]. The end result of the curing phase is a continuous cohesive film that holds the aggregate in place with a strong adhesive bond. Water evaporation can be fairly fast under favorable weather conditions, but high humidity, low temperatures, or rainfall will retard the curing process [1].

Various techniques are used to cure emulsions in the lab including distillation at different temperature with or without the aid of vacuum, evaporation, stirred air flow using nitrogen and many others. A number of emulsion residue recovery techniques were evaluated as part of a study by the Texas Department of Transportation (TxDOT) [4]. The study concluded (based on limited data) that the weathering racks can be considered as the gold standard for recovering the emulsion residues as it mimics field conditions very closely. This study investigated the curing of emulsions on weathering racks as well as in forced draft ovens at moderate temperatures.

2. Objective

One of the major constructability issues related to the use of emulsions in the field is loss of aggregates. Loss of aggregates may be triggered by a number of factors such as improper timing of placement of emulsified asphalt or cover aggregates, insufficient binder to cement the cover aggregates to the existing surface, and allowing fast traffic before proper adhesion is developed. However, the underlying reason for loss of aggregates is due to inadequate development of the adhesive bond between the emulsified binder and the cover aggregate. If the aggregates are placed too late, the emulsion's viscosity would have increased due to partial setting resulting in improper or inadequate coating of the aggregate. Thus, it is necessary to estimate the rate of moisture lost due to evaporation as it will govern the evolution of the mechanical properties of the binder and thus determine the optimal timing for placement of the aggregate after spraying the emulsion. The main objective of this study is to develop a predictive model to quantify the amount of water lost as a function of time and changing weather conditions.

3. Modeling the amount of evaporative water loss

Surface treatment binders generally have an asphalt content ranging between 60% and 70%. Consequently, the emulsion is sufficiently viscous at ambient temperatures which prevent them from flowing when applied on pavements that have elevation differences due to their geometry. However, the preferred application temperature is kept above 55 °C. The higher temperature allows the emulsion to be sprayed without clogging nozzles, to be spread faster and cool more rapidly when it comes in contact with the pavement surface and thus prevents drain-off. Therefore, the amount of water lost to evaporation before the aggregates are spread, occurs in two stages: first while the emulsion cools down from the application temperature to ambient conditions which is then followed by normal evaporation due to convectional heat transfer from the ambient air.

The total amount of evaporative water loss can be modeled as follows:

$$M_{\text{tot}} = M_{\text{cool}} + M_{\text{con}} \tag{1}$$

where M_{tot} = is the total amount of moisture lost, M_{cool} = the amount of moisture lost while the emulsion comes to a thermal equilibrium with its surroundings, M_{con} = is the amount of moisture lost due to absorption of latent heat of vaporization by the emulsion from its surroundings

The following section discusses an empirical approach that can be adopted towards modeling these two different modes of moisture loss from an asphalt emulsion.

3.1. Loss of moisture due to cooling of the emulsion

Emulsions are generally applied at temperatures around 60 °C. In most cases, the applied emulsion will exchange heat with the surrounding environment and during this process the water in the emulsion will absorb the latent heat of vaporization from the internal energy of the system; thus lowering its temperature further. The kinetics of the cooling process will depend upon the specific heat capacity of air and the temperature gradient between the emulsion and its surroundings. The total amount of water vapor that can be generated will be limited by the amount of water that the emulsion had as part of its original formulation. It has been pointed out in the foregoing discussion that the evaporation of water from the emulsion is controlled by the rate of diffusion of the vapor through the asphalt phase as the emulsion starts to break and from a continuous phase. The diffusion barrier will continue to evolve with time as the emulsion breaks and cures which will eventually hinder the evaporation of water from the emulsion. Thus the rate of water vapor will gradually slow down. The total amount of moisture lost while the emulsion is cooling can be modeled as a series of incremental time intervals where each of the intervals can be characterized by:

- The temperature specific to the time interval, which will be lower than its previous time interval due to the cooling process, and
- The amount of water present in the emulsion, which will also evolve with time due to continuous removal of water from the system due to evaporation.

According to the framework of the problem described above, the temperature during the first time interval will be equal to the application temperature for the emulsion and the amount of water in the system will be equal to the water present in the original formulation of the emulsion. Given that the convective heat transfer coefficient of air (k) is known, the duration of this process can be determined using Newton's law of cooling [8]. The total amount of water that will be lost through evaporation during this time interval will be governed by the temperature and the humidity of the surrounding environment. The temperature profile given by Newton's law of Cooling can be used to define the system states at any instant of time. The rate of evaporation at different system states is defined by the temperature and the humidity for that state which can be obtained from experimental data. Together with the temperature profile obtained from Newton's law of Cooling, the evaporation rate determined at different states can be integrated over the duration of this process to compute the total amount of water lost while the emulsion cools down to the ambient temperature.

It should be noted in this context that "k" is dependent on the type of media, gas or liquid, the flow properties such as velocity, viscosity and other flow and temperature dependent properties and therefore needs to be determined for asphalt emulsions from laboratory tests.

3.2. Loss of moisture due to vapor pressure deficit

Evaporation is the transformation of liquid water into a gaseous state and its diffusion into the atmosphere [5]. The evaporation