Cold Regions Science and Technology 106–107 (2014) 1–10

Contents lists available at ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

A road surface freezing model using heat, water and salt balance and its validation by field experiments

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ARTICLE INFO

Article history:
Received 2 October 2013
Accepted 2 June 2014
Available online 9 June 2014

Keywords:
Deicing agents
Road surface freeze prediction model
Heat balance
Water balance
Vehicular liquid dispersion

ABSTRACT

This study aims at helping optimize the application of deicing agents on the winter road surface. In this regard, field tests were conducted for observing how water and deicing agents (=salt) disperse due to passing vehicles as well as for calculating the dissolution rates of salt on the road surface. Additionally, we developed a one-dimensional time-dependent model for the prediction of freezing on a road surface. It takes into account the effects of salting and passing vehicles and is called the RSF-SV model. Its validity was examined by using field test results.

Based on the test results, the relationship between the amount of water dispersed due to passing vehicles and the thickness of the water film on the surface was formulated, and the dissolution rate of salt on the icy road surface was identified. The RSF-SV model used these results for successfully reproducing the time-series changes in the surface temperature, the ice film thickness, the water film thickness, the salt concentration, and the amount of residual salt on the ice-covered road surface after the application of deicing agents.

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1. Introduction

In snowy cold regions, application of deicing agents (hereinafter collectively called “salt”) is widely implemented as an effective measure against snow damage to road. Salt sprinkled on the road surface helps delay ice formation or melt snow and ice by lowering the freezing point of water on the surface. As the freezing point curve shows, the extent to which ice formation is delayed or snow and ice are melt depends on the concentration and the temperature of the salt solution applied. However, the state of the snow-and-ice covered road surface changes with time in various ways at different places. Even very experienced operators sometimes find it difficult to conduct proper salt application under certain weather conditions. Moreover, many cold regions are now facing some potential factors that may adversely affect proper application of salt on winter roads, including the aging and a decrease in the number of operators and cuts in the budget for road maintenance.

In order to maintain the current winter road safety level, development of technologies for supporting optimal salt application will become increasingly important.

Road surface freeze prediction models have been used for supporting salt application operation. The techniques used in these models depend on either statistical methods or physical methods (i.e. heat balance methods). This study focuses on the latter methods.

Road surface freeze prediction models using a heat balance model were actively developed from 1980 through the 1990s (Rayer, 1987; Sass, 1992; Shao, 1990; Thornes, 1984). Many of these models calculate the heat and water balance on the road surface for determining whether the surface is dry, wet or covered with ice film. The heat and water balance is calculated on the basis of melt, freeze, evaporation, sublimation, rainfall, snowfall and water discharge. In the 2000s, research on these models was conducted at many places in the world and various new models were developed (Bouilloud, 2006; Chapman and Thornes, 2005; Chapman et al., 2001; Crevier and Delage, 2001; Knollhoff et al., 2003; Fujimoto et al., 2008; Greenfield and Takle, 2006; Jansson et al., 2006; Takahashi et al., 2006). It is worthy of mention that road surface freeze prediction models were combined with thermal mapping to make prediction of surface conditions possible along a road or in an area instead of at a fixed-point (Chapman et al., 2001). Some road surface freeze prediction models took into account freezing due to frost that often affects bridges and elevated bridges (Greenfield and Takle, 2006; Knollhoff et al., 2003).

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http://dx.doi.org/10.1016/j.coldregions.2014.06.001
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One of the remaining challenges for these kinds of models has been the modeling of anthropogenic factors such as the effects of passing vehicles and sprinkled salt. Recently, thermal effects of passing vehicles on the road surface temperature were incorporated in some models (Chapman and Thornes, 2005; Fujimoto et al., 2008; Takahashi et al., 2006). More recently, the researchers of this study proposed a model that takes into account the effects of the stopping and starting of vehicles at signalized intersections (Fujimoto et al., 2012a).

On the other hand, development of models has not been advanced for simulating the effect of salt on the road surface, and very few road surface freeze prediction models take into account the thermal, physical effects of salt on the road surface conditions. If a road surface freeze prediction model that gives consideration to the effects of salt is available, the model will be useful for predicting the surface conditions after salt application as well as for evaluating the effects of salt application, and thus will be able to help optimize salt application operation. The researchers in this study proposed a road surface freeze prediction model that factored in freezing point depression due to salt. The model was validated in laboratory experiments with regard to the prediction of the freezing process of salt solution under limited weather conditions without traffic (Fujimoto et al., 2012b). In order to apply this model to actual roads, it is necessary to develop a model of simultaneous phase transition of water, ice and salt, a process that involves salt dissolution, and also to quantify the movement of salt on the road surface.

To address these issues, this study aims at:

(i) Evaluating the water and salt transfer on the road surface due to passing vehicles;
(ii) Identifying the effects of the dissolution rate of salt on snow and ice on the surface;
(iii) Developing a Road Surface Freeze prediction model that takes into account the effects of Salting and passing Vehicles (RSF-SV model) that utilizes heat, water and salt balance for analysis and is available for analyzing time-series changes in the thickness of the water/ice film, the salt concentration and the amount of residual salt after spraying solid-phase salt on the road surface; and
(iv) Evaluating the validity of the RSF-SV model in the light of the results of field tests that are conducted for examining the effects of sprinkled salt and passing vehicles.

2. RSF-SV model

2.1. Outline of the RSF-SV model

The RSF-SV model can calculate the time change of the temperature, of the mass of water, ice and salt, and of the thickness and salt concentration of the ice layer on the road surface after salt application in one dimension. This model is innovative in that it combines the effects of salt application (i.e. latent heat and freezing point depression) with conventional road surface freeze prediction models that depend on the heat and water balance on the road surface. This model takes into account the thermal effects given by passing vehicles (i.e. frictional heat flux of tires, radiant heat flux of vehicles, sensible heat flux induced by vehicles, and radiant heat shield by vehicles) and physical effects (i.e. dispersion of salt and water).

Modeling of the simultaneous phase transition of water, ice and salt that takes place after salt application to the ice-covered road surface is shown in Fig. 1. Input factors required for analysis are weather conditions (air temperature, relative humidity, wind velocity, insolation flux, sky radiation flux), traffic condition (hourly traffic volume, vehicle speed), road condition (configuration, thermophysical properties, gradient) and the pavement or ground temperature as the bottom boundary condition. When salt is sprinkled over the ice-covered

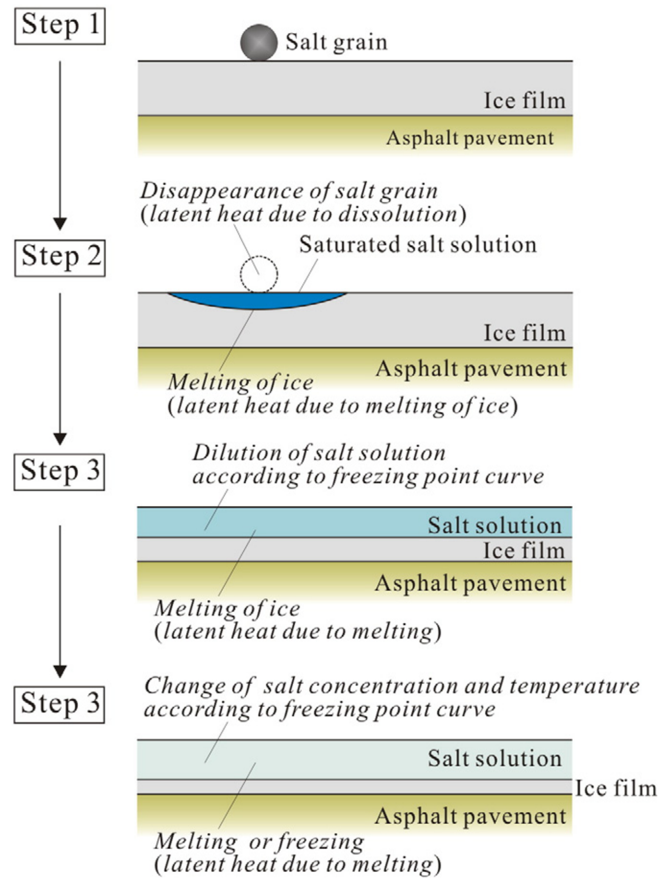

Fig. 1. Phase transition due to salt application to the ice-covered road surface.

surface, the simultaneous phase transition as shown in Steps 1–4 in Fig. 1 occurs.

Step 1: Salt grains come in contact with the ice film.
Step 2: Saturated salt solution generates around salt grains. During the phase transition, the heat of salt dissolution (i.e. heat absorption by sodium chloride and heat generation by calcium chloride) and heat of ice melting are generated.
Step 3: Ice is melted until the salt solution reaches the concentration level at the freezing temperature, and the salt solution is diluted.
Step 4: When the temperature of the salt solution changes due to the heat balance, the concentration of the salt solution changes according to the freezing point curve, and consequently the ice on the surface is melted or water is frozen.

The RSF-SV model predicts the changes in the temperature and the concentration of the salt solution in the process from Step 1 to Step 4 above by analyzing the heat, water, ice and salt balance on the road surface. With this model, it is possible to obtain data on the thickness of the ice/water film, the concentration of salt, and the amount of residual salt on the road surface. The heat, water, ice and salt balance will be explained in Section 3 below.

2.2. Assumptions

The RSF-SV model is based on the following assumptions:

(I) The dissolution flux of salt is constant in time. Technically speaking, the value of the dissolution flux on the ice surface depends on the area of contact between solid salt grains and salt solution as well as on the surrounding salt solution concentration.

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