SIRWEC 2006 25th-27th March, Turin, ITALY

Effects of Tire Frictional Heat on Snow Covered Road Surface

Akihiro Fujimoto[1], Hiroshi Watanabe[2] and Teruyuki Fukuhara[1]

[1] University of Fukui, Japan, Email: afujimot@anc.anc-d.fukui-u.ac.jp
[2] Suiko Engineering Co., Japan, Email: watanabe@suikoken.co.jp

ABSTRACT

For the quantitative understanding of the effects of tire frictional heat and compaction of vehicles on the snow layer on a pavement, a wheel-tracking (WT) test was carried out. According to the WT test, the heat transfer coefficients between a tire and a dry pavement or packed snow surface were obtained beside the snow consolidation due to normal force of vehicle. Consequently, the former was 60W/m^{2}K and the latter was 70W/m^{2}K. The proposed heat balance model well reproduced the snow and pavement temperature and could estimate the snow height melted by traffic.

Keywords: Tire frictional heat, Heat balance, Heat transfer coefficient, Packed snow

1. INTRODUCTION

Methods for forecasting winter road surface conditions are significantly needed to reduce not only traffic accidents but also curtailment of the maintenance administrative expenses, associated with salting, plowing and so forth.

In general, the road surface forecasting model is divided into two categories. One is a stochastic model and road surface temperature (RST) is mainly calculated using meteorological data such as atmospheric temperature and humidity, wind velocity, sky radiation, etc. Nakatsuji et al.[1], Hori[2] and Eros Pasero et al.[3] applied a neural network to the prediction of road surface freezing on temperature.

The other one is a physical model and the RST is calculated by a heat balance of pavement and snow/ice layers on it. Tatiana V. Samodurova[4], J. Shao and P. J. Lister[5], Lee Chapman and John E. Thornes[6] developed a road ice prediction model to calculate the RST from the combination of an unsteady one-dimensional heat conduction equation within the road sublayers and an energy balance equation taking account of the solar irradiance, the long-wave irradiance, the sensible and latent heat, and the ground conductive heat. Although there are many winter road surface forecasting models, there are few models which consider physical or thermal properties of traffic. It is well recognized that tire frictional heat melts a packed snow surface and sometimes causes a subsequent re-freezing, so called 'black ice'. The thermal or physical effect of vehicle, however, has not been fully understood yet. A current study of Fujimoto et al. and Kobayashi et al. showed that the snow density on a road increased with the traffic volume because of the snow consolidation, i.e. the physical effect of traffic and that the snow consolidation caused the decrease in the skid resistance number (A. Fujimoto et al., 2002[7] and T. Kobayashi et al., 2004[8]).

Our study focuses on developing a winter road surface prediction model based on a heat energy balance method to predict the change of snow/ice state of resulting in snowfall - snow consolidation (compacting) - icing - melting, associated with not only road weather condition but also traffic and salting (scattering anti-icing agent). A unique point of the model is that it includes the thermal and physical effects of vehicle on the snow/ice on a road.

This paper describes the heat transfer coefficient between tire and dry pavement or packed snow obtained from the combination of a wheel-tracking test and the winter road surface prediction model and shows the comparison between the test results and the computational results on the packed snow and pavement temperature.

2. EXPERIMENTAL EQUIPMENT AND PROCEDURE

2.1 Wheel-tracking test

A wheel-tracking (WT) test was conducted in a constant temperature room and the room temperature was set up in three levels, i.e., -3, -6 and -10℃. The WT tester consists of a test piece of pavement (W0.3xL0.5x H0.2m), a packed snow on it, a standard tire and a motor to slide the tire (wheel). The snow is made by an ice shaver. The tire repeats a horizontal reciprocal motion on the packed snow surface with a speed of 1.5 km/h and

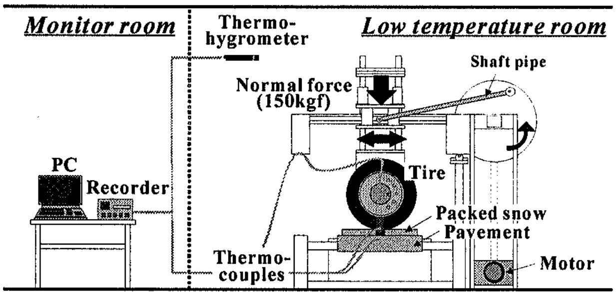


Fig. 1 Apparatus of WT tester

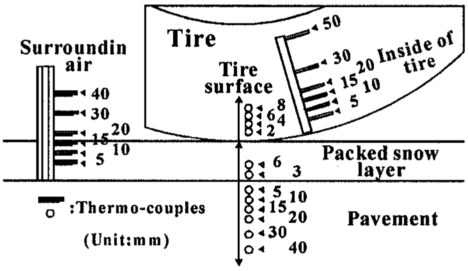


Fig. 2 Positions of temperature measurement

Table 1 Thermal properties of pavement and snow

Thermal properties	Value	Note
Packed snow		
Density (kg/m^3)	Calculated value	measured
Specific heat (kJ/kg/K)	2.1	reference[9]
Thermal conductivity (W/m/K)	—	reference[11]
Injection rate	0.90	reference[9]
Pavement		
Density (kg/m^3)	2544	Mass = 38.0kg, Volume = 0.015m^3
Specific heat (kJ/kg/K)	0.92	reference[9]
Thermal conductivity (W/m/K)	2.06	measured
Injection rate	0.93	reference[10]

the wheel compression force of 150kgf acts on the packed snow layer (see Fig. 1). The procedure of the WT test is as follows:

1. Pack artificial snow, made by the ice shaver, on the pavement so as to become the density of about 350kg/m^3,
2. Slide the tire back and forth on the packed snow surface,
3. Measure the snow density for the number of wheel (tire) passage time of 10, 1000, 3000, 5000 and 9000 times, respectively.

Frictional heat generated by the tire slide (tire frictional heat) is transferred to the packed snow layer and the pavement. This heat transfer can be picked up by thermo-couples mounted in the tire, on the tire surface, in the packed snow layer and in the pavement (see Fig. 2).

The surface condition of the packed snow was recorded by a video camera.

3. HEAT BALANCE EQUATION

The heat balance equation of the packed snow is written as:

$$\frac{\partial I_e}{\partial t} = G - L + S + R_n + S_v \tag{1}$$

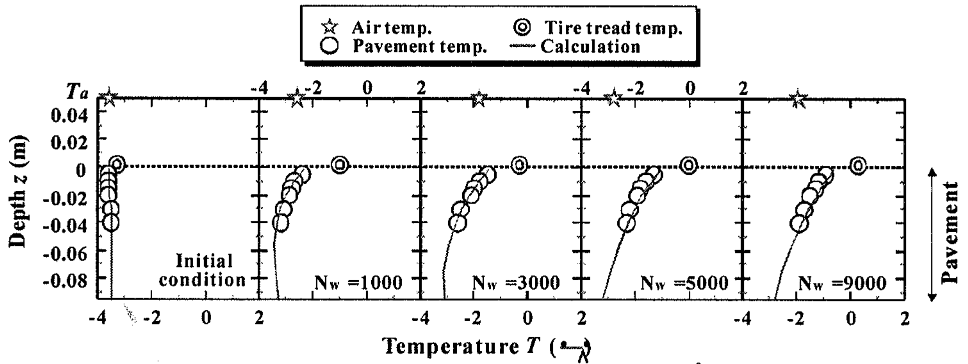
$$S_v = \begin{cases} \alpha_t (T_t - T_{pav}) & \text{for dry surface} \\ \alpha_t (T_t - T_s) & \text{for snow surface} \end{cases} \tag{2}$$

where I_e is the internal energy of the packed snow layer, G is the pavement heat flux by the conduction, L is the latent heat flux associated with sublimation, S is the sensible heat flux associated with air flow, R_n is the net long-wave radiation flux across the pavement or snow surface and S_v is the heat flux transferring between the tire and the pavement or the packed snow, defined by Eq. (2). In Eq. (2), α_t is the heat transfer, T_t is the tire temperature, T_{pav} is the pavement temperature and T_s is the snow temperature. Inserting Eq. (2) into Eq. (1), the snow temperature (or the pavement temperature) is calculated.

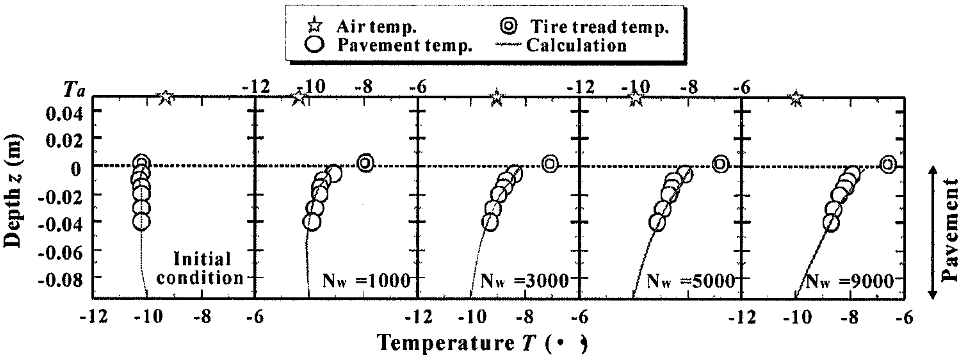
Table 1 shows thermal properties of the pavement and snow used in the computation. The thermal conductivity of snow, λ_s, was given by an empirical formula proposed by Devaux[11], that is

$$\lambda_s = 2.9 \times 10^{-2} + 2.9 \times 10^{-6} \rho_s^{\,2} \tag{3}$$

where ρ_s is snow density. The tire temperature was given from the experiment as a boundary condition.



(a) Room air temperature = -3℃



(b) Room air temperature = -10℃

Fig. 3 Time valuations of tire and pavement temperature (Dry condition)

4. RESULTS AND DISCUSSIONS

4.1 Dry pavement

Fig. 3(a) and Fig. 3(b) show the experimental results of the tire temperature (◎), the dry pavement temperature (•) and the air temperature(☆) in the different wheel passage times (N_w = 1000, 3000, 5000 and 9000) for the air temperature of -3℃ and -10℃, respectively. A solid line means the computational result. Initially uniform pavement temperature rose from the pavement surface, associated with the rise in the tire temperature due to the tire frictional heat. The computational temperature profile agreed well with the experimental one for each case. The heat transfer coefficient between the tire and the dry pavement surface was 60W/m^{2}K for three different air temperatures.

4.2 Packed snow pavement

Fig. 4 shows the change of snow density, ρ_s, due to the passage of the wheel. Plots, blacked out, indicate initial snow density (about 350kg/m^3) and blank plots indicate the snow density caused by wheel compression which is related with the number of wheel passage times. The snow density, ρ_s, suddenly increased to about 600kg/m^3 by the first ten times passage (N_w = 10). After N_w = 1000, the value of ρ_s gradually increased and finally became about 800kg/m^3. When the air temperature was -3℃, the snow density reached about 980kg/m^3. This result from the freezing of the packed snow (see Photograph 1).

Fig. 5(a) and Fig. 5(b) show a comparison of the experimental results of the tire temperature (◎), the packed snow pavement temperature (•) and the air temperature (☆) and computational results in the different wheel passage times for the air temperature of -3℃ and -10℃, respectively.

The snow depth, H_s, is a computational result only and is evaluated as the sum of the snow consolidation due to normal force of vehicle and the snow melting due to the tire frictional heat. The Mass of melted snow (M_m) is calculated using Eqs. (1) and (2), and Eq. (1) is described as follows:

$$(\rho c)_s \frac{\partial (T_s V_s)}{\partial t} = G - L + S + R_n + S_v + M_m L_m \tag{4}$$

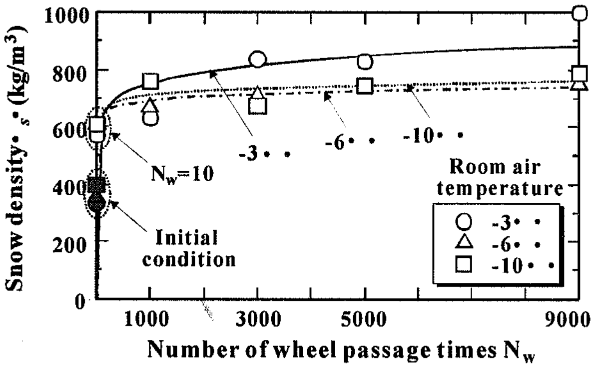
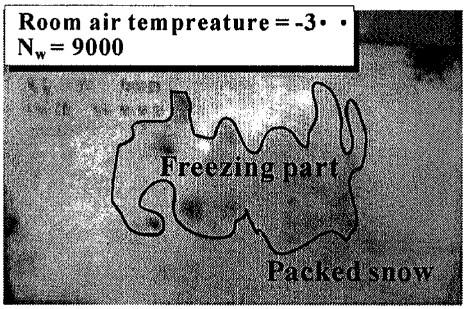
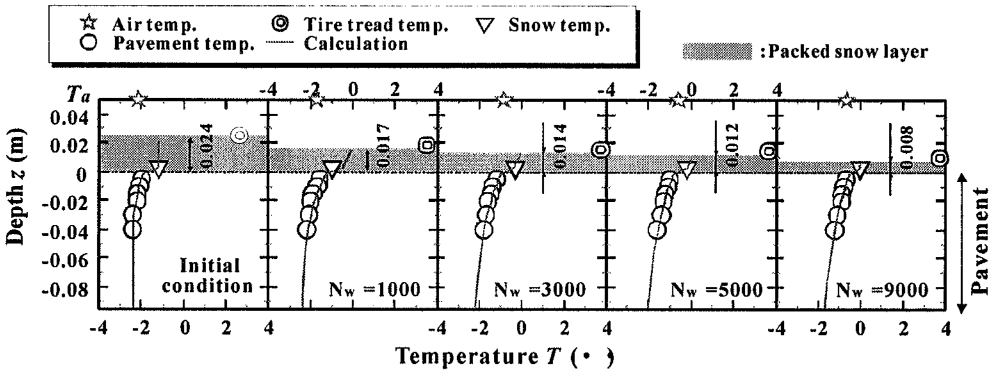


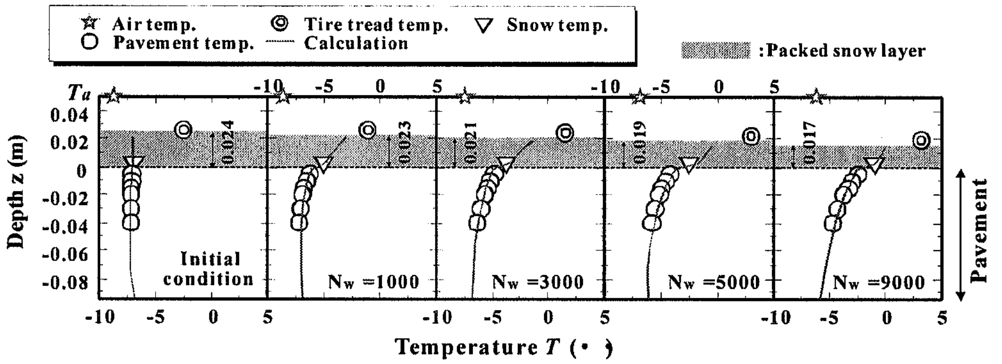
Fig. 4 Change of snow density with number of wheel passage times



Photograph 1 Freezing of packed snow surface due to wheel slide (N_w= 9000, Room air temperature = -3℃)



(a) Room air temperature = -3℃



(b) Room air temperature = -10℃

Fig. 5 Time valuations of tire and snow temperature (Packed snow condition)

in which $(\rho c)_s$ is a composite heat capacity of the ice and water, V_s is the control volume of the packed snow and L_m is the heat of fusion. Since T_s is zero in process of snow melting, from Eq. (4), M_m is calculated by

$$M_m = \frac{-(G-L+S+R_n+S_v)}{L_m+(\rho c)_s T_s/\rho_w} \qquad (5)$$

where ρ_w is the density of water.

The snow temperature rose from -3℃ to 0℃ in N_w = 3000 as for the air temperature of -3℃. In the case of -10℃ (see Fig. 5(b)), the snow temperature reached 0℃ between N_w = 5000 and 9000.

Good agreement of the experiment and computation about the snow and pavement temperature appeared when the heat transfer coefficient between the tire and the packed snow surface was about 70W/m^{2}K.

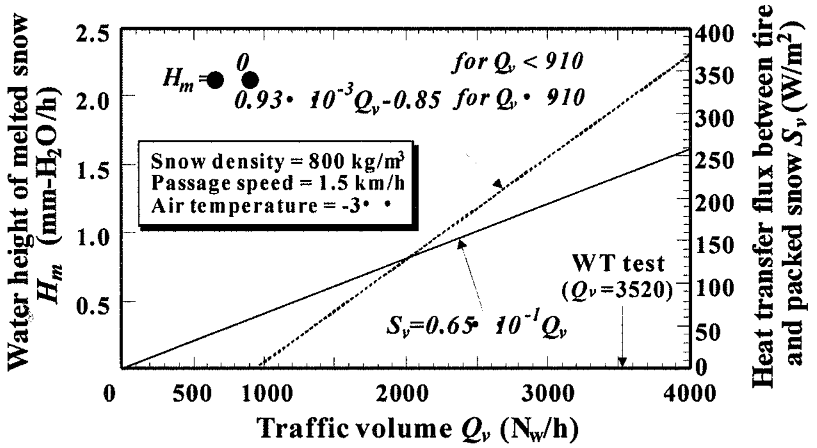


Fig. 6 Water height of melted snow due to heat flux provided from a tire to a packed snow surface under different hourly traffic volumes

5. THERMAL EFFECT OF TIRE OF PASSAGE VEHICLES

Fig. 6 shows the change of the water height of melted snow (H_m) due to the heat flux provided from a tire to a packed snow surface (S_v) under different hourly traffic volumes (Q_v) for air temperature of -3℃ without the solar irradiance. In this calculation, it was assumed that the time rate of vehicle passage is constant and ρ_s keeps 800kg/m^3 to avoid the snow consolidation due to traffic. Q_v means N_w per an hour and was chosen in 0 to 3520. Q_v =3520 is equivalent to the frequency of the sliding motion of tire in the WT test. The computation indicates the result one hour after vehicle passage started. S_v linearly increases from 0 to 230W/m^2 with Q_v. H_m is zero for $Q_v < 910$ because the packed snow temperature does not reach 0℃. The packed snow, however, starts melting for $Q_v \geqq 910$, and H_m is linearly proportional to Q_v. For example, H_m becomes 2.0mm/h when Q_v is 3520. Finally, the relations between Q_v and S_v, and between Q_v and H_m are expressed by the following equations.

$$S_v = 0.65 \times 10^{-1} Q_v \tag{6}$$

$$H_m = \begin{cases} 0 & for\ Q_v < 910 \\ 0.93 \times 10^{-3} Q_v - 0.85 & for\ Q_v \geq 910 \end{cases} \tag{7}$$

6. CONCLUSIONS

A wheel-tracking test (WT test) was carried out to evaluate the heat transfer coefficient between a tire and a dry pavement or a packed snow surface due to the tire frictional heat.

A heat balance model, taken into account of the tire frictional heat, was also introduced in this paper and the effects of the tire frictional heat on a snow road surface were quantitatively described through the decrease in the snow height beside the snow consolidation due to vehicle passage.

In conclusion, the main findings drawn from this study are as follows;

1) The heat transfer coefficients between a tire and a dry pavement surface and between a tire and a packed snow surface are 60W/m^{2}K and 70W/m^{2}K, respectively.
2) The proposed heat transfer model can well reproduce the temperatures of the packed snow and of the pavement obtained in the WT test.
3) The effects of the tire frictional heat on snow covered road can not be ignored when traffic volume is large.

7. REFERENCES

[1] K. Yamakawa, S. Hanaoka, Y. Onodera and T. Nakatsuji. 1996. *Prediction of the slipperiness of a road surface in winter using a Neural-Kalman filter.* Cold region technology conference. 12. 189-194.

[2] Manabu Hori. 2004. *Road ice prediction models in snowy area using neural network.* International Conference on Snow Engineering. 5. 23-27.

[3] Eros Pasero et al. 2004. *Neural Meteorological Forecast.* International Road Weather Conference. 12.

[4] Tatjana V. Samodurova. 2000. *Models for short-term road ice formation forecast*, International Road Weather Conference. 10.

[5] J. Shao and P. J. Lister. 1996. *An automated forecasting model of road surface temperature and state for winter road maintenance.* Journal of applied meteorology. 35. 1352-1361.

[6] Lee Chapman and John E. Thornes. 2002. *A blueprint for 21^{st} century road ice prediction.* International Road Weather Conference. 11.
[7] A. Fujimoto et al. 2002. *A numerical model for road icing estimation used by heat energy balance method –Heat transfer between tire, compacted snow layer and road surface–*. Cold region technology conference. 18. 71-76.
[8] T. Kobayashi, K. Kosugi, T Sato, S. Mochizuki and A. Sato. 2004. *Consolidation process of snow on roads by vehicles.* International Conference on Snow Engineering. 5. 29-32.
[9] Warren M. Rohsenow. 1998. *Handbook of heat transfer.* McGraw-Hill.
[10] Yunus A. Cengel. 2002. *Heat transfer –A practical approach–*. McGraw-Hill.
[11] Dorsey, N. E. 1940. *Properties of ordinary water substances.* Reinhold.