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An evaluation of the ice melting during concrete-ice abrasion experiment

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ABSTRACT

The process of ice melting during abrasive interactions with concrete is essential in a variety of contact phenomena. In this paper, we refer to abrasive tests for different samples of concrete with roughness in the range of 9–35 μm. The experimental conditions were: 1 MPa ice pressure, ambient temperature −10 °C, average sliding velocity 0–0.16 m/s. Using the experimental logs, we balance the heat transfer in the ice-concrete contact zone to compute the amount of molten ice. The average melting of ice varies from 3 to 29% of total ice consumption. The highest melting rate of ice corresponded to the lowest ice consumption and lower average abrasion of concrete. The theoretical calculations are validated against benchmarked commercial software with an in-house melting model.

1. Introduction

Concrete-ice abrasion is a degradation of the concrete surface under ice sliding and impact. The laboratory simulation of the process accounts for pressure between ice and concrete, sliding interaction, and moderate heating of the concrete surface against icing. Sliding friction and surface heating may facilitate the melting of ice. In addition, wet contact and temperature gradient influence the pore pressure of concrete [1] and thermal stresses in the contact zone [2]. These influence the concrete-ice abrasion.

The melting of ice during the concrete-ice abrasion test has been described in works [2,3] and reviewed that the pressurized melting occurs for temperatures above −2 °C [1]. There it is demonstrated that the melting reduces with ambient temperature (ex. −10 °C) and the contact sliding velocity (ex. five cm/s) [1]. However, melting ice in the contact zone is a part of the laboratory experiment that has not yet been quantified. In this work, we present a theoretical study of melting based on laboratory results [4] and numerical simulation. We show that up to 29% of ice melts during the abrasion experiment and thus reduces the degradation of concrete. The mechanical impact with less ice melting demonstrates larger abrasion of the concrete surface.

2. Abrasion experiment and theoretical model of melting

The experimental setup simulated the sliding of the ice sample on the concrete block surface. A cylinder of freshwater ice has a

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diameter of 73.4 mm and a height of 160 mm. The concrete sample is a slab: L 300 mm x W 100 mm x H 50 mm. The concrete mix was self-compacting, high-performance concrete, with cube compressive strength 90 MPa at 28 days and had a water-cement ratio of 0.42, with substituting 2% of silica fume. There were different tested concrete surfaces: mold concrete surface, rough sand-blasted, and sawn.

The ice sample was given 1 MPa pressure towards the concrete surface. The average sliding velocity was 0.16 m/s. The total sliding distance of ice was 3 km, achieved with 13–43 ice samples consumed per one concrete sample. The air temperature was set at −10 °C. The moderate heating of the concrete sample protected it from icing [3]. The surface temperature of the concrete sample was set between 0 and -2 °C using a temperature-controlled cooling liquid circulating in the metal base plate of the concrete sample holder.

The ice sample was placed tight in the ice sample holder (with the same diameter of 73.4 mm). There were two typical scenarios during the experiment: low ice consumption with the water film formation on the concrete surface and high ice consumption with spallation and ice slush on the concrete surface.

2.1. Theoretical approach

There are several thermal effects responsible for the melting of ice in the contact zone. The primary source of heat Q_f is due to the friction of the ice sample over the concrete. Supplementary heating comes from the thermostabilized surface of concrete Q_h. The destruction of the ice at the contact generates ice particles whose temperature is lower than the temperature of the contact. They remove heat Q_i from the surface of the concrete. A conservative assumption sets the coldest temperature in the ice to the ambient temperature T_a. The theoretical melting rate of ice due to the friction heat, "warm" concrete surface, and cooling from ice was calculated as follows:

$$\frac{dH}{dt}=\frac{Q_f+Q_h-Q_i}{L\,\rho\,S}=\frac{\mu\,\mathrm{F}\ \ \mathrm{v}+S\frac{k}{\delta}(T_b-T_t)-S\,\dot{h}\,\rho\,C_p(T_a-T_i)}{L\,\rho\,S} \tag{1}$$

Where: L - latent heat of crystallization; ρ - density of ice; S - an area of contact surface; μ – the experimental value of the coefficient of kinetic friction; v - average ice velocity; F - vertical ice load; k - thermal conductivity of concrete; δ - the height of the concrete sample; T_b - temperature of concrete at the bottom of the sample; T_t - temperature of concrete at the top of the sample; T_a - ambient temperature; T_b - temperature of ice formation; $\dot{h}$ - ice consumption rate; C_p - ice specific heat.

To validate the theoretical model (1), a numerical model of an ice sample melting was developed. In this model, we applied a standard melting-solidification routine available in Siemens STAR-CCM+ [5]. The routine, based on the mixture multiphase model, solves the energy equation for both ice and liquid water:

$$d\rho_m h\big/_{dt}=\Delta(kT), \tag{2}$$

where ρ_m is the density of the mixture of the phases, h is the enthalpy of the phases, and k is the thermal conductivity of the mixture.

The boundary condition at the bottom of the ice cylinder included the thermal sources Q_f, Q_h, and Q_i from the theoretical model (Eq. (1)). In addition, using Ranz-Marshall's expression [6], a forced convective boundary was set on the sides of the ice cylinder to mimic the heat transfer to the environment for the moving ice cylinder. The computational grid consisted of $5.7\cdot10^6$ computational cells. The cells were 0.1-mm high in an axial direction; they were coarsened to 1 mm in a radial direction. Central differences were used for the spatial discretization, and the temporal discretization was done using Euler's implicit scheme with a time step of 10 ms.

3. Results

The average theoretical melting of ice varies from 3 to 29% of the total ice consumed during the test. The numerical simulation and the theoretical model (1) correlate well with each other. The results from both models are presented in the Table 1 below.

The numerical model returns 0.8–14.5% lower rates. The observed difference is due to the supplementary cooling of the side surface of the ice.

The ice consumption was also varied based on two typical scenarios with ice spallation and without. These scenarios varied within one tested surface for different ice samples. The concrete sample with a higher frequency of spallation is one with higher total ice consumption and vice versa. Fig. 2 shows the correlation between total ice consumption and theoretical melting during 3 km of concrete-ice abrasion test for six samples. There is high ice consumption (i.e., more spallation present) that corresponds to lower ice melting. The spalled-away ice cools the contact zone more efficiently due to a particle-increased contact area and the more efficient heat removal towards the coldest parts of the ice sample. Fig. 1 demonstrates the temperature distribution predicted by the numerical model. The figure shows a significant subcooling of the sample sets at the vicinity of the warm bottom. Therefore, subcooling the contact zone by approaching cold layers of ice is expected due to the mechanical removal of ice from the heated zone. Fig. 3 shows the correlation between the rate of concrete-ice abrasion and the melting rate of ice. The abrasion of concrete is higher for samples with a

Table 1
Melting rate predicted numerically and theoretically.

Sample	Mold B75 (1)	Sand-blasted B75 (1)	Sawn B75 (1)
Numerical	20.0%	5.8%	9.0%
Theoretical	34.5%	7.8%	9.8%

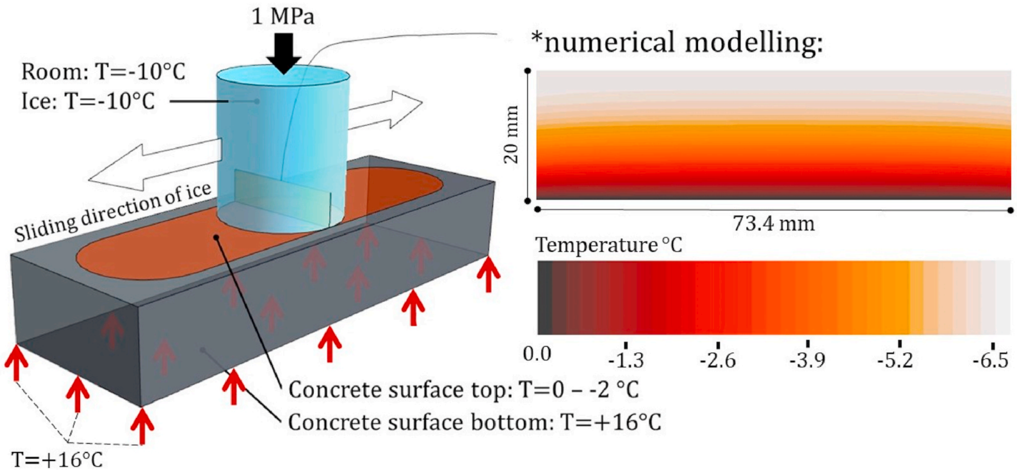

Fig. 1. Scheme of concrete-ice abrasion sliding test. Insert numerical modeling results of temperature profiles in the midline of the ice sample.

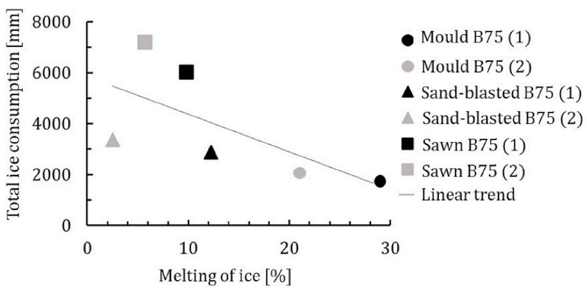

Fig. 2. Theoretical average melting rate vs. total ice consumption during 3 km of the sliding test.

lower melting rate. Fig. 4 shows that the melting rate becomes lower for concrete surfaces with higher average surface roughness.

4. Discussion

The experimental results are significantly scattered due to a wide variety of mechanical properties of ice. However, for concrete samples with the same type of surface, the results are comparable.

The experiments with the same concrete mix and different tested surfaces show correlations with the theoretical ice melting. High ice consumption corresponds to a lower ice melting (Fig. 2). That can be seen as at high ice consumption, ice was consumed more for mechanical interaction with concrete and abraded concrete surface. Also, its spallation during the test at high ice consumption contributes to a lower temperature at the contact zone.

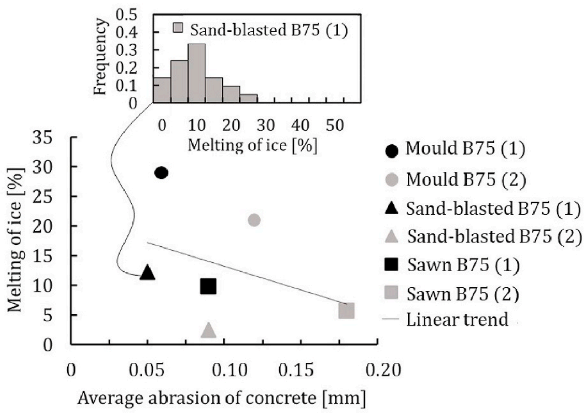

Fig. 3. Correlation between concrete-ice abrasion after 3 km sliding test and melting rate of ice.

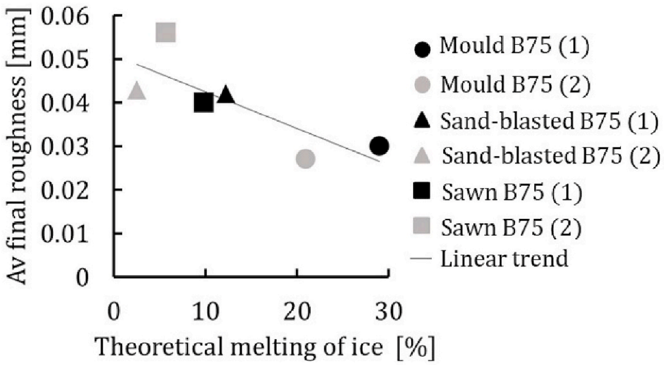

Fig. 4. Theoretical average melting rate vs. average roughness of concrete surface after 3 km of the sliding test.

Lower ice melting corresponds to a higher average abrasion depth as the strength of the ice in the colder conditions is higher (Fig. 3). It shows that the concrete surface has been worn more when the ice melts less. Figs. 2 and 3 together indicate that abrasion is connected to the mechanical degradation of ice rather than melting.

The results of the melting analysis in Fig. 4 show a correlation with the average roughness of the concrete surface after the 3 km test. The melting is lower for higher average roughness and higher for lower roughness, presumably due to an increase of the instantaneous contact surface with a lower roughness profile.

5. Conclusion

The concrete ice abrasion study [4] investigated mechanical interaction between the two materials, ice, and concrete as a cause of surface degradation. In this study, we show that ice melting during the experiment can contribute to lower abrasion of concrete by investigating a theoretical model of ice melting during the concrete-ice abrasion test. The model demonstrated that molten ice could go up to 29% of the total ice consumption. Such intense melting is an essential part of what happens during the ice-concrete sliding interaction.

Author statement

Guzel Shamsutdinova: Conceptualization, Methodology, Investigation, Writing
Saidkomil S. Saidmurodov: Investigation, Data Curation.
Stefan Jacobsen: Conceptualization and Supervision of the experiments.
Max A. N. Hendriks: Conceptualization and Supervision of the experiments.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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