Changes in the Structure and Thermal Conductivity of Crushed Ice Frozen Backfills

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Abstract. Crushed ice backfills are widely used in the regions of the North. There, in natural conditions in winter, it can be easily prepared for the subsequent arrangement and repair of damaged temporary road surfaces, sealing cracks in the ice layer, backfilling with over-ice water and for the formation of ice refrigerant reserves in refrigerated food storage facilities.

1. Introduction
In the process of using loose backfills of specially formed round granules or pieces of crushed ice, an increasing compaction of the initial structure of the loose backfill occurs. It is accompanied by a decrease in the total porosity, an increase in the actual contact spot of contacting granules or pieces of ice, strengthening of the newly formed composite layer and an increase in effective thermal conductivity in the process of consolidation of the initially bulk layer. The majority of publications are devoted to the analysis of the mechanical properties of bulk inhomogeneous structures in the process of their creation, consolidation and operation [1,2]. The thermophysical properties of such fillings and the dynamics of their change in time have been studied much less [3,4].

The data required for a quantitative assessment of the determining parameters influence on the consolidation process and the change in effective thermal conductivity include: the density of ice \( \rho_{\text{ice}} \) and the backfill layer \( \rho_{\text{fill}} \), the average size of granules or pieces of crushed ice \( d = 2r \), the surface tension coefficient \( \gamma(T) \), the activation energy of diffusion processes \( E_{\text{act}} \), the kinematic viscosity \( \nu_k \), plastic strain ratio \( \sigma_{\text{pl}}, \tau_{\text{eq}} \) - equivalent time of plastic flow skipping and ice backfills storage duration \( \tau \) [3].

Knowledge of the required data makes it possible to estimate the relative size of the contact spot \( y = (r_{\text{cont}} / r_{\text{granule}}) = f (r, T, E_{\text{act}}, \tau) \) and the effective thermal conductivity \( \lambda_{\text{eff}} = f (\lambda_{\text{ice}}, \rho_{\text{ice}}, \rho_{\text{fill}}, \tau, y) \).

The review works show that the simultaneous occurrence of a number of processes during consolidation and the lack of information on the cumulative effect of these processes do not allow to recommend unified generally recognized analytical dependences for calculating the contact parameters. And, therefore, approximate relations of varying degrees of complexity and accuracy are used. Usually, the information about the parameters of the contact spot is obtained indirectly - from experimental data on the kinetics of changes in strength \( \sigma_{\text{str}} (T, \tau) \), electrical resistivity \( \rho_{\text{el}} (T, \tau) \) or other properties.
The error in estimating the relative area of the contact spot according to the recommended ratios can be from ±15-25% at P <0.5 and increase noticeably with increasing porosity.

To estimate the relative radius of the actual contact spot of the backfill particles at the initial moment, the following expression is proposed [4]:

\[ y = \frac{r_{\text{cont}}}{r} \approx (1 - P)^{3/2}. \]  

(1)

During the consolidation time \( \tau \), the growth of the actual contact spot is described by the expressions [3]:

\[ y(\tau) \approx 2 \left[ \frac{y^2 r^2}{\sigma_p \nu_k} \tau \right]^{1/4} \]  

(2)

for viscous flow, and

\[ y(\tau) \approx 2 \left[ \frac{y^2 r^2}{\sigma_p \nu_k} (\tau + \tau_{ep}) \right]^{1/4} \]  

(3)

for quasi-viscous (with plastic strain) flow.

Since the parameters \( r, y, \sigma_p, \nu_k, \tau_{ep} \) are usually known with a rather significant error (20-50%) or are not known at all, the simplified relations of the following form are recommended for practical use [3]:

\[ y(\tau) \approx \text{const}(\tau)^{1/n} \]  

(4)

The value of \( n \) fluctuates within a significant range of \( 4 \leq n \leq 7 \), depending on the considered models of the consolidation process. For example, in the model of consolidation due to bulk diffusion, \( n = 5 \), and if consolidation occurs due to surface diffusion of atoms, then the value is \( n = 7 \) [3]. Relation (4) is fulfilled with an error of ± 15% in a wide range of changes in the porosity of the consolidating backfill 0.3 <\( P <0.9 \).

Analyzing the set of experimental data on the thermal conductivity of consolidated ice backfills, Smorygin GI [3] drew attention to the fact that with the same values of the density (porosity) of the backfill, the discrepancy in the measurement results can reach more than 300%, which significantly exceeds the experimental error. By a series of specially designed experiments on ice backfills of different porosity and significantly different holding times (from 10 minutes to 30 days), the author of [3] confirmed that the nature of the change in the actual contact spot during the consolidation of the ice backfill is well described by relations of the form (2) - (4).

When processing the results of measurements of thermal conductivity in the process of consolidation, in [3], the values of the activation energy, time dependence degree parameter and a pre-exponential coefficient were obtained. To estimate the relative radius of the actual contact spot \( y_r \), taking into account environmental conditions \( T \), particle sizes \( r = 0.5d \) (cm) and consolidation time \( \tau \) (seconds), the following relation is proposed [3]:

\[ y_r(\tau) \approx \left[ \frac{\tau}{27T} \exp \left( \frac{-6200}{T} \right) \right]^{1/5}. \]  

(5)

Substituting the obtained values of the actual contact spot into the model of a granular bound material, we obtain the desired value of the effective thermal conductivity of the consolidating backfills of ice granules or crushed ice [4]:

\[ \lambda_{\text{eff}} = \lambda_{\text{ice}} y_b (y/4)^2, \]  

(6)

\[ y_b = 2 \left[ (N_b - 1)/N_b \right]^{0.5}, \quad N_b = [P + 3 + (P^2 - 10P + 9)^{0.5}]/2P \]

\[ P = 1 - (\rho_{\text{ice}}/\rho_{\text{ice}}), \quad y_4 = y_b/(1 - \Pi)^{0.5}. \]

It is valid in a wide variation range of the parameters related.

The results of calculations using formulas (5) - (6), presented in Figure 1, are in qualitative and quantitative agreement with the collected experimental data of the Russian and foreign researchers in.
the range of changes in the consolidated backfills density of $300 < \rho_{\text{fill}} < 550 \text{ kg/m}^3$, porosity $0.4 < P < 0.7$ and holding times - from 600 sec to 30 days.

![Figure 1. Change in thermal conductivity of ice backfills in the process of ice consolidation. Experiment: 1 - Kondrat'eva Ya S [3]; 2 - de Weix [3]; 3 - Van Dassin J. [3]; 4 - Johnson A. [3]. Calculations by the model of a loosely bound granular material [4] taking into account the size of the actual contact spot $y_f (5)$: 9 - $\tau = 600 \text{ s}$; 10 - $\tau = 1 \text{ day}$; 11 - $\tau = 30 \text{ days.}]

2. References

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