THE COMpressive STRENGTH OF CONSOLIDATED PARTS
OF ICE RIDGE MODEL

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ABSTRACT
In cold region, given that first-year ice ridges often govern the design load for offshore
structure, it is important to obtain knowledge about ice ridges, especially the
consolidated parts, in designing offshore structures. In this study, we performed a
preliminary series of tests (uniaxial compression tests) in the laboratory on model ice
(refrozen rubble) to investigate the strength and physical properties of the consolidated
parts. In order to construct the consolidated parts of ice ridge model, cubical ice blocks
of size were randomly arranged in the ice tank filed with saline water that had greater
salinity than that of the ice blocks. After they were refrozen, we collected core sample
from ice ridge model by cylindrical drills with various diameters. And we performed the
uniaxial compressive test with various combinations of core diameters and
representative length of ice block. In addition, we performed test by changing the strain
rate and room temperature, when \( d = 100 \text{ mm}, a = 42.5 \text{ mm} \).

INTRODUCTION
An ice ridge is formed when ice blocks or rafted ice, which have been produced by
sliding, pressing, and buckling of ice, are vertically piled up. The magnitude of the ice
block varies, ranging from several tens of centimeters to several meters. The structure
of the ice ridge consists of a sail above the sea level and a keel below the sea level.
Moreover, the keel consists a consolidated part around the water surface, and an
unconsolidated part of the lower part. Its consolidation mechanism includes pressure,
latent-heat and heat-transfer consolidation which depends on the configuration, size,
void and porosity of the sail and ice block, as well as meteorological conditions such as
temperature (Prodanovic, 1979). Yet, its internal structure and heat balance is so
complicated that they are not known clearly. As the design load of an offshore
structure in an ice-covered sea area is often given by this first-year ice ridge
understanding the strength properties of its consolidated parts where each ice blocks are

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re-frozen is particularly important. Up to now, a consolidated parts has been often assumed to have one to two times the thickness of and the same strength as its surrounding level ice. Many laboratory tests and field tests have so far been performed on the unconsolidated parts, which is regarded as Mohr-Coulomb material, and the internal friction angle or cohesion, etc. has been measured to examine a characteristics of the shear strength in the unconsolidated parts (Wong, 1986; Leppäranta et al., 1989). However, because restrictions and difficulties exist with the experimental techniques and requirements, few cases of research into the strength properties of a consolidated part are recognized as systematic research. Among them, Rogachko et al. (1999) carried out indentation tests and compression tests inside and outside the laboratory to examine the consolidated part model, and Rogachko et al. (1997) carried out laboratory tests to examine the strength of hummock, in particular considering the void effects. In this study, which specifically focuses on the consolidated part of ice ridge, an uniaxial compressive test was conducted by artificially building a simplified ice ridge model (re-frozen rubble) as a laboratory experiment. Specimens were built up by combining various values of representative length of ice blocks and core diameter, and a systematic experiment was performed to find the strength properties and failure mode. In addition, we performed tests by changing the strain rate and room temperature, when \( d = 100 \text{ mm} \), \( a = 42.5 \text{ mm} \). And we investigated the strength properties by changing strain rate or temperature.

**EXPERIMENTAL METHODS AND REQUIREMENTS**

The structure and mechanical characteristics of an actual ice ridge are complicated as they are affected by the fracture process, configuration, size, void among ice blocks, and so on. Furthermore, they vary in time and place. Therefore, since there are a lot of difficulties to ideally conduct experiments for the natural ridge, somehow we should simplify the phenomena and deal with this problem by using an appropriate model. In this study, ice blocks, which were randomly arranged in a tank filled with saline water, were refrozen with the water, and this ice structure was investigated as an ice ridge model. Here, we call the part (spaces) among ice blocks as “void” (the voids in this study are frozen). Also, by comparing the ice ridge model with level ice, which was also produced in identical conditions, the basic properties of ice ridge model were identified. Production methods of the ice ridge model are as follows.

1. A mesh-type square frame with bore holes at the bottom was placed in a container with 10 ‰ saline water. After freezing the water to a certain level of thickness, many cubic ice blocks with representative length \( a \) were removed from the frame.
2. To make the temperature of each ice block constant, the ice blocks were left on a sheet for one day.
3. A tank with 25 ‰ saline water was cooled up to around freezing point.
4. When the temperature of the tank reached near freezing point, ice blocks were put in to a certain depth of the tank. After a pile of ice was consolidated to a certain level of thickness (about 10 days), it was taken out of the tank.

Level ice was produced from 10 ‰ or 25 ‰ saline water in the same tank in which the ice ridge model were produced. All ice ridge models were produced under the same conditions (room temperature, water depth, freezing duration). And the coring direction and location of the ice core sample are shown Figure 1. The reproduced ice ridge models were physically tested with various combinations of core diameters (cylindrical
specimen) and ice blocks size (case 1), as shown in the Table 1. And to measuring the salinity, density, strain rate and uniaxial compressive strength, the failure mode was identified by a video and a camera.

In addition, we performed the strain rate changed in the range of $1 \times 10^{-5} \sim 3 \times 10^{-2}$ sec$^{-1}$ (case 2), the sample temperature changed in the range of $-7 \degree C \sim -15 \degree C$ (case 3), when $d = 10$ cm, $a = 42.5$ cm. In addition to our previous experiments on “The Physical Properties of Consolidated Ridge Ice modeled as Frozen Rubble” (Kioka et al., 2001), “Tests on Strength of Consolidated Parts of Hummock Ice Model” (Yasunaga et al., 2001)

| Table 1: Experimental conditions |
|----------------|-----|-----|-----|
| Case | 1 | 2 | 3 |
| Temperature | $-10 \degree C$ | $-7, -10, -15 \degree C$ | $-10 \degree C$ |
| Strain rate | $1 \times 10^{-3}$ sec$^{-1}$ | $1 \times 10^{-3}$ sec$^{-1}$ | $1 \times 10^{-3} \sim 3 \times 10^{-2}$ sec$^{-1}$ |
| Specimen diameter | $d = 4.5, 7.5, 10, 15, 30$ (cm) | $d = 10$ (cm) | $d = 10$ (cm) |
| Specimen height | $2 \times d$ | $2 \times d$ | $2 \times d$ |
| Representative length of ice block | $a = 2.25, 35, 4.25, 7.5, 10$ (cm) | $a = 4.25$ (cm) | $a = 4.25$ (cm) |
| Sample size of the collected specimen | 4 ~ 10 for each same case | | |

![Figure 1: Core sample direction](image)

**TEST RESULTS**

$\sigma_v$ and $\sigma_h$ indicate the average of compressive strength of the vertical core samples and that of the horizontal core samples. $\sigma_{hu}$ and $\sigma_{hl}$ indicate the average of compressive strength of the horizontal core samples on upper and that of lower parts, respectively.

**Macroscopic isotropy in the ice ridge model strength**

In the case of level ice, $\sigma_v$ is greater than $\sigma_h$, and $\sigma_{hu}$ is greater than $\sigma_{hl}$. Generally, level ice shows anisotropy, in which the strength varies depending on the direction of the crystallographic axis and the size of the crystals. In other words, the strength of level ice is affected largely by the direction and location of ice.

While ice ridge model does not show much difference wherever the ice is located or directed. Thus it can be supposed that the ice ridge model in the experiments has no
specific alignment and no specific crystal size, since pre-crystallized ice blocks are randomly arranged and voids among ice blocks freeze up from the part close to the ice blocks.

**Failure mode (strain rate was $10^{-3}$ sec$^{-1}$)**
The failure mode was identified by eye, as well as using video. With level ice, the specimen collected perpendicular to the ice growth direction (horizontal core sample) was brittle and showed explosive shear failure, while many vertical cuts were observed in the specimen collected parallel to the ice growth direction (vertical core sample). This was similar to the well-known failure mode. However, specimens of the ice ridge model showed the same failure mode independent of the direction and location, and also showed like a more ductile failure mode (particularly at $100$ mm $> d$). Cracks occurred in various locations such as the inside and interface of ice blocks, but dominant cracks of the fracture were not identified by eye or video. However, because the each size of ice fragments due to fracture was mostly comparable to the size of the original ice block, the interfacial fracture and the fracture in the void are assumed to be primary fractures.

**Uniaxial compressive strength for ice ridge model with volume of core sample ($V$) to volume of ice block ($Va$).**
We considered the strength of ice ridge model depends on ratio of core diameter ($d$) and representative length of ice blocks ($a$): $d/a$. From the result, the strength tends to be low when $d/a$ is close to 1 or less than 1.

This section discusses relationship the strength and $V/Va$: ratio of volume of core sample ($V$) to volume of ice block ($Va$).

Figure 2 shows strength of the ice ridge model versus $V/Va$ for each diameter $d$ of core sample. Except the cases of small $V/Va$ (less than about 50) and very large $V/Va$, the analysis of variance shows little effect on strength of the change in $V/Va$. When $V/Va$ is close to 50 or less than 50, the strength tends to be low. In case that the diameter of core sample was small relative to ice block size, a flat and continuous block surface, including an interface between a block and a void, will be dominant or visible in the specimen since the ice blocks are almost cubical. Hence, the specimen will cause a failure easily due to such surface or interface. And then, the strength also depends on orientation of the surface or interface. When $V/Va$ is less than about 50, the scattering in values of strength increases. When $V/Va$ is close to 1, the strength corresponds to that of the ice block itself. However, because there is a chance that some samples may include a block surface, the strength is expected to differ greatly by sampling location even for the same $V/Va$. Hence,
where \( V/V_0 \) is less than about 50, the mechanical strength appears to depend heavily not only on the ice's essential characteristics but on the ice conditions, including a block surface orientations in the sample.

**Size effect**
Generally, strength tends to decrease as the size or volume of a material increases. It is known that latent microscopic defects or cracks increase relatively with the size of material. We observed this size effect in the current test results. Also it seems that both strength coincided with each other when the size was fully large.

**Relationship between uniaxial compressive strength and strain rate of an ice ridge. (Table1, case 2)**
Uniaxial compressive strength tests were also performed in the range of \( 1 \times 10^{-5} \) to \( 4 \times 10^{-2} \) sec\(^{-1} \) to investigate the relationship between compressive strength and strain rate. Herein, the specimen with a diameter of 100 mm, a representative length of ice block (a) of 42.5 mm and its temperature of \(-10^\circ C\) were tested. The results are shown in Figure 3. As can be seen in the figure, the strength of the ice ridge tended to increase as the strain rate increased and reached a peak when strain rate was about \( 4 \times 10^{-4} \) sec\(^{-1}\) (Figure 3(a)). We also performed the same test on level ice (Figure 3(c) and (d)). The strength of level ice reached a peak when strain rate was \( 4 \times 10^{-4} \) sec\(^{-1}\).

![Figure 3: Relationship between compressive strength and strain rate (\( \dot{\varepsilon} \))](image-url)
Failure modes
Figure 3(b) shows the stress-strain curve of ice ridge model with change in strain rate. In areas (1) and (2) of Figure 3(a), ice ridge model showed ductile failure, and in area (3) of Figure 3(a), the ice ridge model showed brittle failure. When strain rate was small, failure occurred in the voids and interfaces of the ice block. However, in the case of large strain rate or brittle failure, the failure was not influenced by the voids and interfaces of the ice blocks.

On the other hand, the level ice showed brittle failure in areas (2), (3) of Figure 3(a). Thus, the strengths in both ice ridge and level ice have a maximum value at a same strain rate, but their failure modes were different each other.

Relationship between uniaxial compressive strength and temperature of an ice ridge model (Table 1, case 3)
Figure 4(a) shows the relationship between strength and temperature of the ice ridge model. The strength shows each average respectively. Herein, the specimen with a diameter \(d\) of 100 mm, a representative length of ice block \(a\) of 42.5 mm and its temperature were tested. The strain rate was \(10^{-3}\) sec\(^{-1}\). As shown in the figure, the strength of the ice ridge model tended to increase as the temperature decreased. This result is similar to previously reported results for level ice.

Failure modes
Figure 4(b) shows the stress-strain curve of ice ridge model for each ice temperature. When ice temperature was \(-7\) °C ice ridge model showed ductile failure. Crack appeared in the voids and interfaces of the ice blocks, and compressive strength was low. When ice temperature was \(-15\) °C, brittle failure occurred. It seems that the voids and interfaces of the ice blocks had no effect on cracking.

CONCLUSION
1) The strength of level ice is affected largely by the direction and location of ice, while ice ridge model does not show much difference wherever the ice is located or directed.
2) Except the cases of small \(V/Va\) (less than about 50) and very large \(V/Va\), it was little effect on strength of the change in \(V/Va\). When \(V/Va\) is close to 50 or less than 50, the strength tends to be low.
3) The strength of the ice ridge model and level ice decreased gradually with the increase of the size of the sample. When the size was fully large, both strength coincided with each other. Namely, the strength showed the size effect.

4) The strength of the ice ridge model and level ice reached a peak when strain rate was about $4 \times 10^{-4}$ sec$^{-1}$.

5) When strain rate was small ($10^{-5}$ sec$^{-1}$) and close to $4 \times 10^{-4}$ sec$^{-1}$ the failure mode of ice ridge model showed ductile failure. And the failure occurred in the voids and interfaces of ice block. However in case of strain rate was large or brittle failure, the failure was not influence of void and interface of ice blocks.

6) The strength of the ice ridge model tends to increase as the temperature decreases. When ice temperature was $-7 \, ^\circ C$, ice ridge model showed ductile failure. Crack appeared in the voids and interfaces of the ice blocks, and compressive strength was low. When ice temperature was $-15 \, ^\circ C$, brittle failure occurred. It seems that the voids and interfaces of ice blocks had no effect on cracking.

REFERENCES


