

COMPRESSIVE STRENGTH OF COMPACTED MACHINE-MADE SNOW

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ABSTRACT: Compacted snow holds a significant role in both structural engineering and terramechanics in cold regions. Machine-made snow makes indoor snow-related mechanical experiments possible throughout the year, fostering the pace of engineering research. This paper presents an experimental program to investigate the uniaxial compressive behavior of compacted machine-made snow. Machine-made snow was produced in different air temperatures into two types – wet snow and dry snow – and snow cylinders were fabricated to different densities, from 450 kg/m³ via a layer-by-layer filling technique to over 700 kg/m³ by ramming, showing an ice-like appearance. Four compressive loading rates (1 mm/min, 10 mm/min, 25 mm/min and 100 mm/min), covering both ductile and brittle failure regimes, were mainly investigated in the experimental program with a temperature of -10°C. The tested specimens featured a two-stage growing trend of compressive stress under significant deformation at the loading rate of 1 mm/min. In contrast, higher compressive loading rates shifted the specimen behavior towards brittleness with more uncertainty and diverse failure modes, as demonstrated by some load-displacement curves that display a zig-zag fashion. To better characterize the mechanical behavior of snow for engineering analysis and construction, new definitions of compressive strength and modulus are proposed and the values are calculated. The compressive strength of snow shows an increasing relationship with snow density, especially when the density is close to 700 kg/m³. Additionally, some phenomena in the experiment are discussed including the non-linearity at the initial stage of compression and the ductility differences between wet and dry snow.

KEYWORDS: machine-made snow, compressive behavior, compressive strength, compressive modulus, failure modes.

1. INTRODUCTION

In cold regions, construction practices involve the utilization of natural materials, including compacted snow and ice, to attain desired structural outcomes. Prior to actual construction, indoor laboratory testing plays a crucial role in understanding the performance of compacted snow structural components. As the mechanical properties of compacted snow are crucial in predicting large-scale structure behavior, there is a need for further investigation. Machine-made snow, with its uniform microstructure and year-round availability, serves as an ideal material for preparing compacted snow and verifying the structural integrity of snow-based elements. An experimental program was thus conducted to examine the uniaxial compressive strength of compacted machine-made snow. An essential aspect of understanding the mechanical properties of compacted snow in this study is analyzing its uniaxial compressive behavior, specifically the compressive strength and modulus.

2. EXPERIMENTAL METHOD

2.1 *Preparation of snow specimens*

Fresh machine-made snow, was produced by a snowfall machine and fell into a chest freezer, possessing an initial density of around 300 kg/m³. There were two types of fresh snow produced in different temperature conditions. In one type, first investigated, the snow was collected at room air temperature, which melted the periphery of the snow crystals and made the fresh snow more dynamic. The snow consisted of snow crystals, air pores, and liquid water, with initial snow temperature of about -1°C. This type of snow is called 'wet snow' in this paper. Another type of snow, latterly studied, fell into the chest freezer in a cold atmosphere of around 5°C. The colder and dryer air alleviated snow melting before entering the freezer, and its corresponding snow temperature was close to -2°C. The term 'dry snow' is employed in this paper for this kind of snow that had a dryer, more uniform and sand-like quality. Fresh dry snow in this study resembled white sugar in appearance.

Subsequently, the snow was carefully filled into pre-cooled plastic molds with an inner diameter of 70 mm and an inner height of 150 mm by hand

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in a layer-by-layer fashion, shaping it into cylinders, meanwhile resulting in various densities.

Some molds were firstly filled with snow by hand wearing pre-cooled thick gloves and then additionally densified through ramming using a rammer specified in ASTM D698 or extra compressing by hand via a small round plate. The number of blows was not specified or recorded for each specimen during the preparation, as the mold and the test method have not been standardized yet. Though, it was clearly felt by the authors that the latter rammings brought less compaction effects into the specimen, as the density already reached a high level. Each rammed specimen consumed much more snow, requiring several times of snow replenishment by hand during the intervals of ramming. Particularly, for wet-snow rammed specimens, as the ramming was conducted also in room temperature outside the freezer, the melting during ramming was more salient than the dry-snow counterparts rammed in the 5°C air temperature. The splash of water and snow from the interspace between the rammer and plastic container was observed especially during the impact compaction for wet-snow rammed specimens. The very top layer of rammed snow specimens could not be much rammed because of snow spills. Still, the authors strived to compress the snow manually during the final snow replenishment. No matter whether rammed or not, as the plastic molds had no caps, all the specimens' tops were finally covered with extra snow in case of possible specimen damage during later storage and moving.

After being stored in a -10°C freezer for over 24 hours, the upper surfaces of snow cylinders were firstly smoothened by removing the additional snow cover using a metal knife and abrasive papers. Then the specimens were demolded by hand. The warmth and slight squeeze from hands to the mold created a very thin circle of gap between the snow specimen surface and the plastic's inner surface. After demolding, the specimens were swiftly weighed on an electronic balance and put back into the freezer, meanwhile labeled and covered with tied-up plastic bags, a similar measure taken by Wu et al. (2020).

Once cooled again, the snow cylinders were prepared for compressive tests. The densities of the snow specimens were calculated, revealing two density ranges, subsequently referred to as middle-density (400-700 kg/m³) and high-density (over 700 kg/m³) in this study.

The pre-test observations of snow cylinders helped to eliminate a few specimens that were not well prepared or demolded. The inspection also revealed some nonuniformity of snow specimens, especially for wet-snow specimens and

rammed specimens. As the water content of fresh wet snow was relatively higher, wet-snow samples often presented an ice-like texture at the bottom, leaving a snow-dominated appearance at other parts. Besides, abrasive paper smoothening slightly melted the top surfaces of all the snow specimens. There were brown parts on rammed specimens as the rammer was slightly rusted. Different from the ice-like part at the bottom of some un-rammed specimens, the rammed specimens resemble an ice cylinder overall, though a few interfaces were noticed, implying the density differences between layers that were rammed.

Displacement-controlled test programs were employed in this experiment, corresponding with previous work by Wang et al. (2021), Lintzén and Edeskär (2015) and Kinoshita (1967). Four different loading rates were principally investigated in this experimental program, which are 1 mm/min (corresponding strain rate 1.11×10^{-4} /s), 10 mm/min (1.11×10^{-3} /s), 25 mm/min (2.78×10^{-3} /s) and 100 mm/min (1.11×10^{-2} /s), respectively. The loading rates were carefully selected based on existing research conducted and summarized by Wang et al. (2021), expected to encompass failure modes that are associated with ductile and brittle behavior. In addition, there were two compressive tests with a loading rate of 5 mm, trying to draw a clearer line between ductile and brittle failure.

A total of 47 snow cylindric specimens were tested in this study. The designations of each specimen are presented as follows. For Specimen No. of I-XXX-YY-Z, I/II represents the type of snow being investigated, I denotes wet snow while II represents dry snow. Meanwhile, XXX and YY denote density (kg/m³) and loading rate (mm/min) respectively. If two specimens share the same density and loading rate, Z in the specimen number helps to discriminate the specimens. If the specimen was rammed to increase the density, (Ram) will appear after the snow type index of I or II.

2.2 Uniaxial compressive testing

The compressive tests were performed in a low-temperature test chamber set at a temperature of -10°C, as Figure 1 shows. Dry ice was also used to aid in creating and maintaining the cold environment, helping to cool the chamber and the loading ends. Every time after sample installation and take-out, in-chamber temperatures took some time (usually less than 30 min, less than 15 min when dry ice was employed) to recover to the preset -10°C, depending on the weather conditions and the chamber performance. A pair of pre-pressed thin wooden plates were placed at the surfaces of the upper and lower compressive plates for better heat insulation. They also offered

proper friction at the loading ends, preventing the snow specimen from sliding away in case of partial melting under compression. The thin wooden plates were marked by lines so that the snow cylinder could be placed right at the center of the loading end. As Figure 2 exhibits, there was a gap deliberately left between the upper end of the specimen and the loading end before the formal compressive test, as pre-compression introduces creep phenomenon and density changes, polluting the actual mechanical behavior of snow confronting external loading.

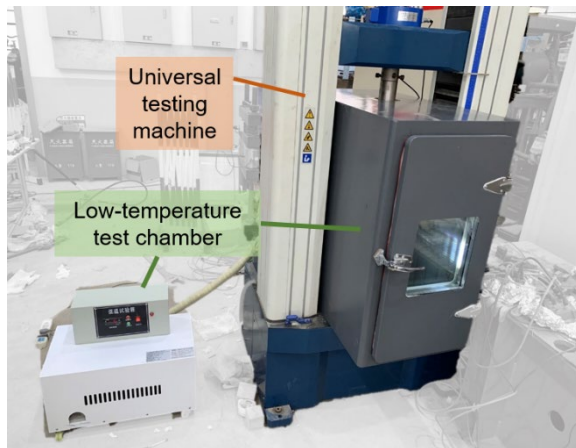


Figure 1: Test equipment and setup

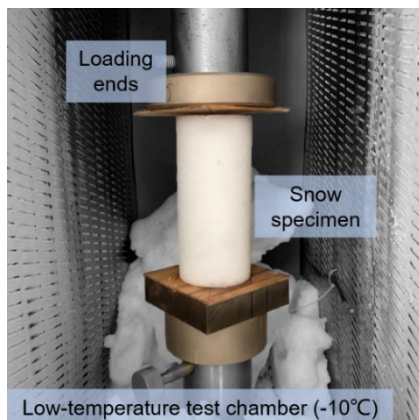


Figure 2: Snow specimen ready for the compression test

A universal test machine with a maximum capacity of 50 kN was deployed in this experimental program. The test machine exerted loading by moving a beam rigidly connected to the upper loading end. Throughout each test, a transducer integrated into the test machine system automatically recorded the load and displacement data at a frequency of 10 Hz. Due to the possible signal noises, the force output data was not precise 0 before the upper loading end touched the snow, the initial stage of all the test data was truncated, and a load of 40 N, which is relatively small compared to the maximum load, is considered the point when the upper loading end built complete

contact with the snow specimen. All of the specimens were planned to be compressed by about 50 mm.

3. EXPERIMENTAL RESULTS

3.1 *Diverse failure modes*

Diverse failure modes were observed on the specimens even with the same density description and loading rate. However, similarities within each loading rate test group allowed for categorization.

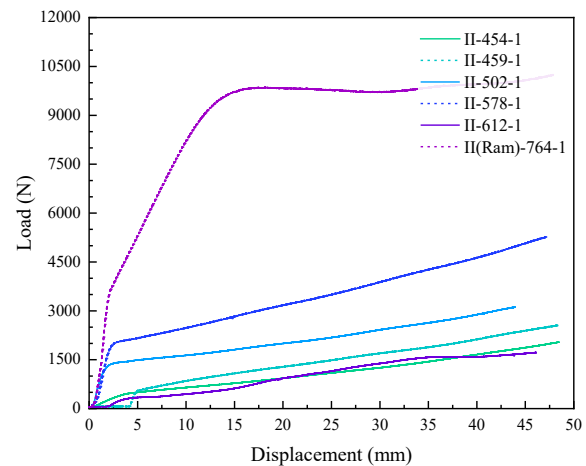


Figure 3: The overall load-displacement curves of dry snow specimens at the loading rate of 1 mm/min

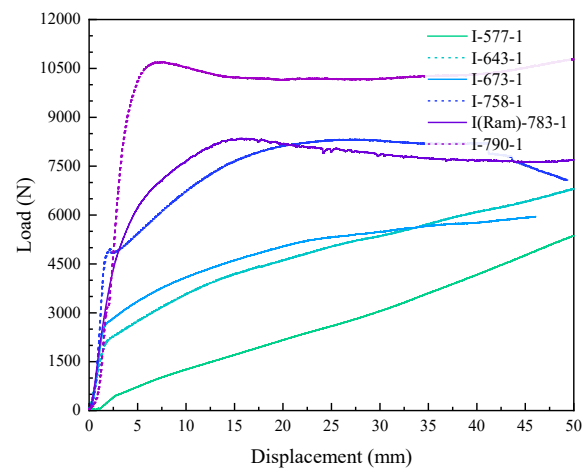


Figure 4: The overall load-displacement curves of wet snow specimens at the loading rate of 1 mm/min

The ductile regime was predominant at low loading rates. For middle-density specimens, defining 'failure' was challenging since these specimens exhibited continuously growing stress-strain curves under compression as Figure 3 shows, meanwhile transversely expanded. After drawing parallel lines with the same interval (25 mm) as references, visual observations revealed that nonuniformity existed within some of the snow

cylinders: some specimens could be compressed uniformly, whose layers showed similar compression and lateral expansion; in contrast, quite a large amount of specimens could not maintain even compression, in which often one or two layers consumed most of the deformation, leaving the adjacent color lines closer, while other layers showed relatively limited compression and horizontal expansion. As for these unevenly compressed specimens, often the final appearance resembled circular steel tubes with local buckling behavior under compression, though the elephant-foot-like part might emerge at various heights of the snow specimen, as Figure 5a) shows as an example.

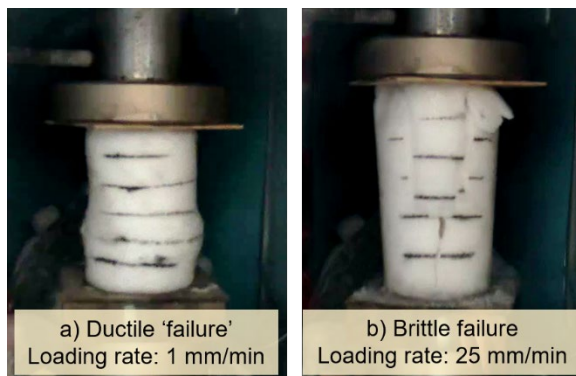


Figure 5 Typical failure modes of snow specimens: a) Ductile 'failure'; b) Brittle failure

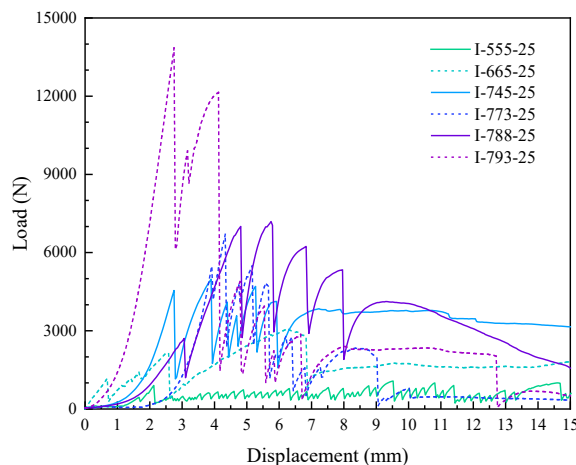


Figure 6: The initial 15 mm load-displacement curves of wet snow specimens at the loading rate of 25 mm/min

Additionally, although the specimen was centered before the formal test, some samples demonstrated lateral displacement at one end or in the middle. This was guessed to be partially due to the nonuniformity within the snow, which caused the stress flow to deviate from the expected vertical direction. Additionally, the loading ends were not designated to completely constrain the horizontal deformation in case over-

constraint might increase the strength of the sample, considering that snow is a material highly dependent on hydrostatic pressure.

The stress-strain curves of high-density specimens exhibited similarities to ice at a low loading rate, as Figure 4 demonstrates, in which a steep ascending curve was followed by a plateau, close to an ideal elastic-plastic model.

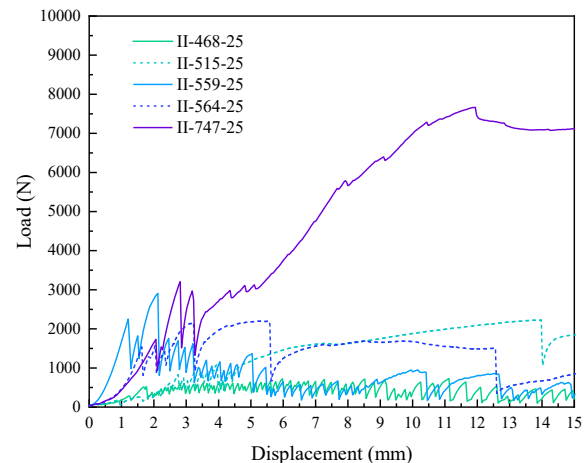


Figure 7: The initial 15 mm load-displacement curves of dry snow specimens at the loading rate of 25 mm/min

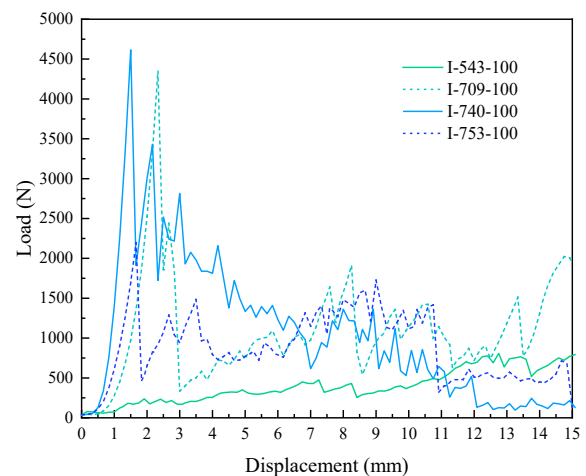


Figure 8: The initial 15 mm load-displacement curves of wet snow specimens at the loading rate of 100 mm/min

In contrast, the brittle regime dominated the failure modes of high-loading-rate specimens (25 mm/min and 100 mm/min). Cracks and fractures appeared in the snow cylinders during compression, resulting in recurring very steep drops in stress-strain curves with a zig-zag pattern, which can be seen from Figure 6 to Figure 9. Brittleness introduced more variation when describing the failure modes of the specimens. Some samples exhibited local failure at the loading ends, while fracture happened in some cylinders, decomposing the snow elements and creating more slim columns. Oblique cracks also appeared in some

tests, cutting the snow cylinder into several pieces, often the upper part above the oblique cracks rived the lower part of the snow, and Figure 5b) is a typical example.

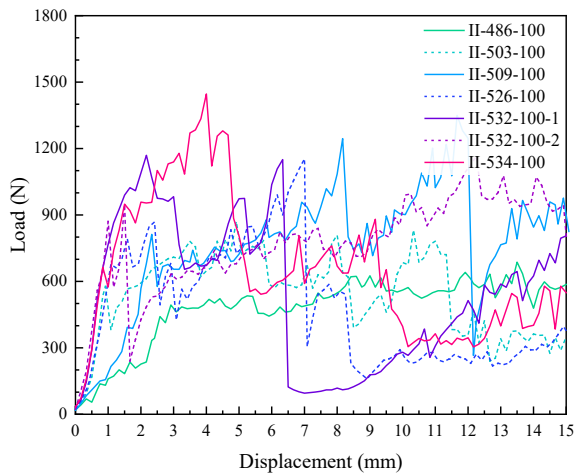


Figure 9: The initial 15 mm load-displacement curves of dry snow specimens at the loading rate of 100 mm/min

From the curves in Figure 6 to Figure 9, the difference between wet and dry snow can be further discussed. The wet snow, usually with a higher density, in which ice clusters might exist, shows more brittle behavior compared to the dry snow within the same ‘brittle description’. In the curves of wet snow specimens, often the force dropped drastically without later fluctuating plateau which can be seen in some dry-snow specimens. Wet-snow specimens possess a higher maximum load with a disadvantaged ‘ductility’ under high loading rates compared to dry snow. Dry snow has a more uniform appearance with no ice-like locations, indicating less strain concentration and a more even compression between the layers and inside the snow sample when resisting the external load.

Additionally, some specimens displayed a failure mode within the ductile-brittle transitional range with a loading rate of 5 mm/min (5.56×10^{-4} /s) to 10 mm/min (1.11×10^{-3} /s), usually characterized by a relatively smooth decrease in stress during compressive failure (Figure 10), especially within wet snow at a loading rate of 10 mm/min. The deformation revealed that the creep of snow behaved a bit during the compression, though often insufficient compared to 1 mm/min-loading rate specimens. For wet snow, the brittleness of snow behavior at high loading rates becomes dominant in the transitional rate range. The ultimate failure is a competition between the ductile and brittle behavior of the specimen’s intrinsic characteristics, often more uniform and less dense snow (dry snow) would unleash more ductility during compression as there is less stress or strain concentration within the microstructure. As Figure 11

presents, some dry snow specimens showed an ascending behavior that was similar to the ductile ones after the load dropped at the beginning, presenting mixed characteristics on the load-displacement curves.

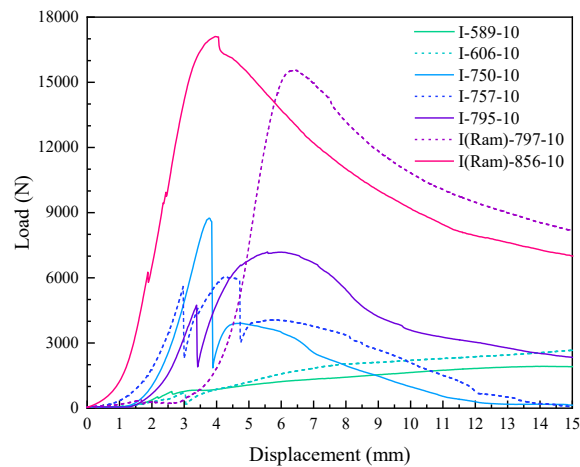


Figure 10: The initial 15 mm load-displacement curves of wet snow specimens at the loading rate of 10 mm/min

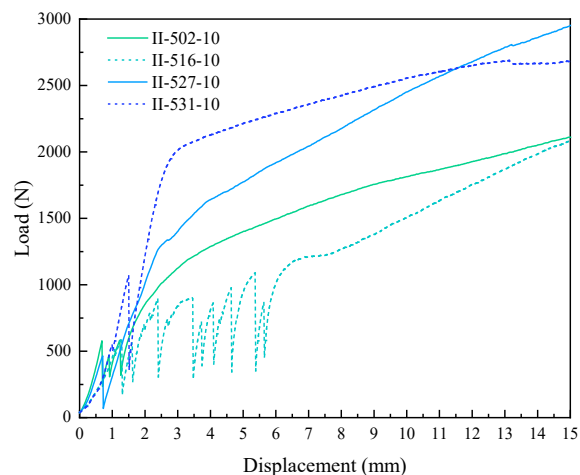


Figure 11: The initial 15 mm load-displacement curves of dry snow specimens at the loading rate of 10 mm/min

3.2 Compressive strength and modulus

In this study, the mechanical behavior of compacted snow is characterized by two parameters: compressive strength and modulus. However, the definitions of the two parameters on the load-displacement curves need a more detailed explanation to cater to the diversity of snow failure modes and engineering applications.

Compressive stress can be characterized in two ways: one is the maximum stress of the specimen along the overall compression. It is a simple idea though it sometimes fails to serve engineering purposes. The maximum stress for ductile behavior usually represents the resistance under the final compressive displacement, as Figure 3 and

Figure 4 show. The corresponding stress at such large deformation betrays engineering applications, where often the maximum bearing capacity is analyzed under a small deformation assumption. Besides, for the specimens with a brittle failure, as the loading ends moved in a relatively quick fashion, the maximum stress often appears after the first drop of the stress-strain curve, at a stage where in fact several snow parts divided by the cracks in the snow cylinder instead of an intact snow element offered the resistance toward the displacement-controlled loading. Thus, the maximum stress is an unveracious and insecure mechanical parameter delineating the snow strength, no matter for the ductile or brittle regime. In this paper, we recommend a snow strength definition that is termed 'turning point stress'. For brittle failure, turning point stress is the stress value at the moment when the load first drops, close to the definition of crushing strength. It should be noted that if the load-displacement curve demonstrates a drop at a force that is below 10% of the maximum load of the whole loading process, the drop will be pardoned to better utilize the mechanical property of snow while maintaining proper safety redundancy for the structure.

For ductile failure, as the snow changed its slope of load-displacement curves on a specific point under slow compression, the corresponding stress of the turning point is considered a better evaluation of the snow strength, borrowing the idea of yielding from metal strength characterization. For metals like steel, its elastic modulus can be easily determined by calculating the slope of the stress-strain curve before the material yields. However, for snow the compressive deformation is mainly irreversible, thus the term elastic modulus is inapplicable. What's more, frequently observed were the non-linear parts at the beginning and sometimes also the end before the turning point of the stress-strain curves for both low- and high-loading-rate specimens, which adds more complexity when calculating the compressive modulus of snow samples. Tentatively, this paper puts forward two modulus calculation methods, trying to better characterize the ascending mechanical behavior of snow under compression from the perspective of structural engineering. The data processing was automated by a code script to improve the analysis efficiency and eliminate human error.

Modulus, method A: All of the load-displacement data points are used for linear regression to figure out the slope, and then the slope value is transformed into modulus by considering the snow cylinder dimensions. This modulus value takes the non-linear parts at the beginning of the stress-

strain curves into account, which often decreases the modulus value mathematically.

Modulus, method B: The data points that are from the 30% of the turning point load to the turning point itself are included for linear regression to calculate the slope. This modulus value mainly describes the linear ascending part of the snow compression load-displacement curves, omitting the response of snow when it is 'insufficiently compressed'.

An explanation of the non-linear behavior at the initial stage of load-force curves could be that heterogeneity in the snow sample created 'weak layers', a term borrowed from avalanche research, which features loose snow and very soft mechanical behavior. When under compression, as a part of a series of springs, weak layers consume the loading end displacement at first and become compacted. After the weak layer shares a similar density with the main body of the snow sample, every snow layer starts to resist the compression equally, and the load-displacement curve could ascend with a higher and more stable slope.

It should be noted that the strength value or modulus of different loading rates cannot merge into a more universal value. Though structural engineering commonly focuses on the static bearing capacity of a structure, due to the viscoelastic nature of snow, the strength value, no matter the maximum stress or the turning point stress, of 1 mm/min-loading-rate snow specimens, should not be considered the most proper value for civil engineering purposes. The strength value and deformation properties of snow should be chosen from various loading-rate data according to the actual scenario. It is hard to define the snow behavior in avalanches, subjected to impact loading and under static compression using a single set of parameters.

Figure 12 to Figure 15 visualize the relationships between the snow density and the maximum stress, the turning point stress, modulus (method A) and modulus (method B), respectively. It is noteworthy that the figures discriminate the data from different loading rate groups by arranging different symbols to the data points. Besides two data points from the 5 mm/min-loading-rate group, more angles on the symbol represent higher loading rates.

Generally, although there is a huge variance in the data, it can be found that there is a positive correlation between the density of the snow and the mechanical properties including the maximum stress, turning point stress and two differently defined moduli. The wet snow generally possessed a higher density compared to dry snow. The ice clusters inside the wet snow specimens, frozen from the liquid water of fresh wet

snow and implied by the specimens' partial ice-like appearance, contribute to the denser structure.

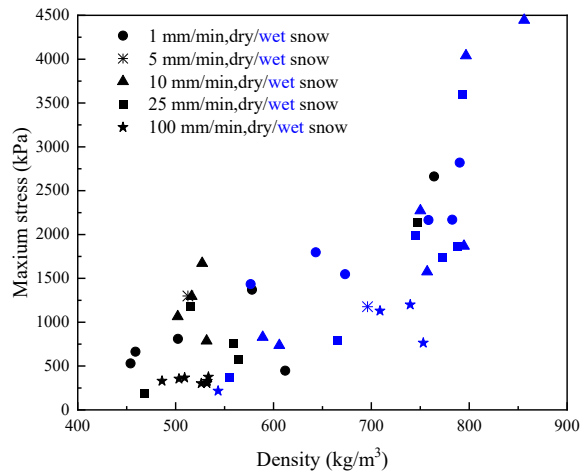


Figure 12: Relationship between maximum stress and density of snow specimens

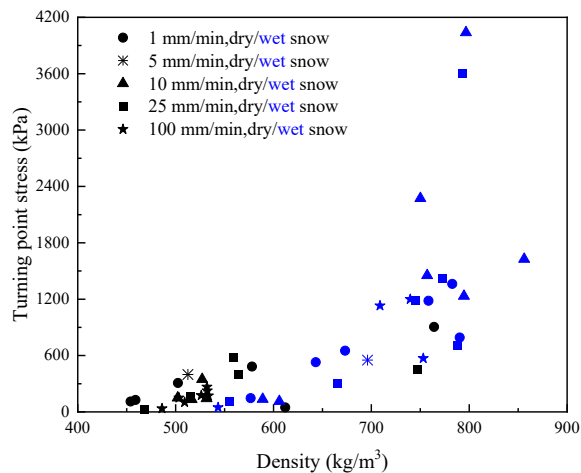


Figure 13: Relationship between turning point stress and density of snow specimens

There is a salient difference in the data between middle-density snow specimens (400-700 kg/m³) and high-density (over 700 kg/m³) ones. The similarities to the ice of high-density specimens make themselves exhibit higher values on all four mechanical parameters. While the difference within the two density groups, respectively, is less conspicuous. The modulus value from method B is overall higher than the modulus value from method A. If the explanation of the 'weak layer' is valid, the modulus value from method B is a better way to delineate the actual deformation properties of a more homogenous snow specimen. Turning point stress is generally lower to maximum stress, retaining more safety redundancy when serving as a strength parameter for snow-related structure design.

Figure 16 and Figure 17 try to present the complex relationships between the loading rates and the two strength values. In this paper, loading

rates instead of strain rates were considered a primary parameter to correspond with the experimental design of existing research conducted by Lintzén and Edeskär (2015) and Wang et al. (2021), also partly because the nonuniformity in the snow sample introduced strain concentration under compression, which might invalidate the concept of 'average strain rate'. It should be noted that the loading rates are plotted on a logarithmic axis for better graph presentation and this measure corresponds with the work of Wang et al. (2021). In this experimental program, 10-mm/min- and 25-mm/min- loading rates present the highest strengths, especially in terms of the maximum stress for high-density specimens. This finding is in agreement with the summarization from Wang et al. (2021). As the data demonstrates variance, in the future statistical methods can be applied to further characterize the trend and provide a more rigorous mathematical result.

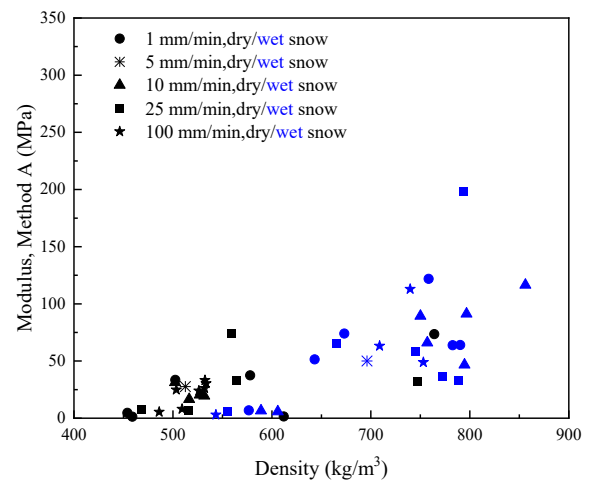


Figure 14: Relationship between modulus (Method A) and density of snow specimens

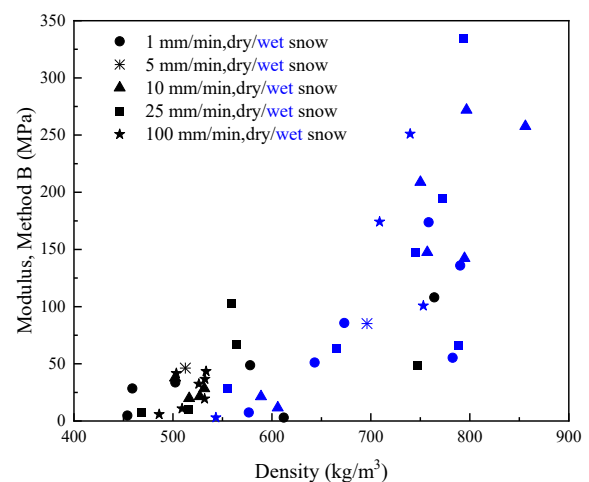


Figure 15: Relationship between modulus (method B) and density of snow specimens

The peak of strength correlated to loading rates could probably be explained by the viscous characteristics of snow. Under very low displacement-

controlled compression, the rheology of snow performs well and the snow microstructure deformation causes salient stress dissipation and more compaction. The snow shows good ductility at this loading rate at a cost of lower strength. Higher loading rates suppress the development of the snow's viscosity, simultaneously forestalling further compaction of snow during the compression process. Elastic behavior dominates under rapid loading, showing strong brittle characteristics, thus cracks and fractures inside the snow sample cause the force drops and a lower strength value.

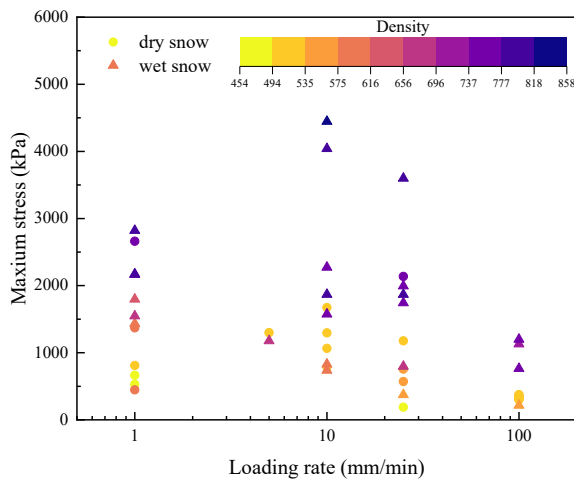


Figure 16: Relationship between the maximum stress and the loading rate

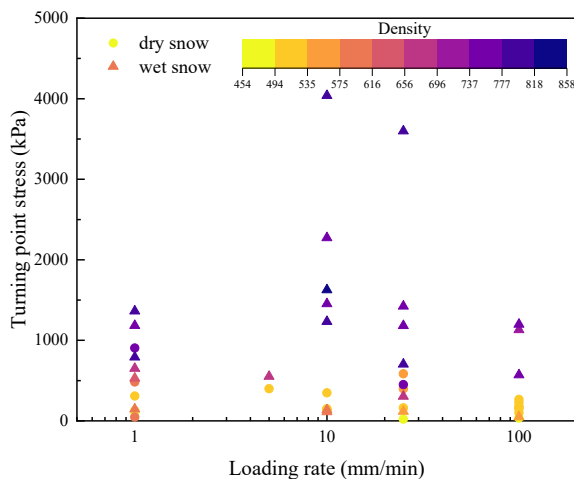


Figure 17: Relationship between turning point stress and the loading rate

4. CONCLUSIONS

This paper presents an experimental program of uniaxial compression tests on snow, considering the snow types, density and loading rate. The experimental procedure is elucidated and the data of some mechanical parameters is reported. Failure modes are described and some explanations are given as well. The highlights and conclusions of this paper include:

- Though variance exists, the strength of compacted artificial snow, delineated no matter by maximum stress or turning point stress, increases with the density of snow. When surpassing 700 kg/m^3 , high-density snow demonstrates a salient improvement compared to middle-density snow. The resemblance to ice of high-density snow is possibly an explanation.
- The strength of snow rises and then decreases as the loading rate accelerates, peaking between 10 mm/min to 25 mm/min . Compressive loading rates below 5 mm/min display ductile failure, while those $\geq 25 \text{ mm/min}$ exhibit brittle failure. A transitional behavior appears at around 10 mm/min . Brittle failure showcases more variability than ductile failure.
- Wet-snow specimens, regardless of failure mode, tend to be more brittle than dry snow. Increased nonuniformity within wet-snow specimens contributes to this brittleness, as denser and irregular ice clusters introduce strain concentration during compression, accelerating fractures in the microstructure. Besides, inhomogeneity between snow layers and inside specimens partly explains snow's nonlinear behavior during initial compression.
- For future applications, definitions of compressive strength and modulus are discussed. A novel parameter, turning point stress, is suggested for snow strength assessment. Two moduli and their calculations are explained. Depending on safety priorities and structural analysis methods, different definitions of compressive strength and modulus can be employed.

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