

# Authors' Responses

Dear reviewer:

Thanks for reviewing the manuscript "Experimental Investigation of the Direct Shear Strength Parameters of Compacted Snow". The manuscript has been carefully revised and improved according to your comments. **In addition, beyond the original density range of 450 to 650 kg·m<sup>-3</sup>, we have supplemented the experimental data by including tests with initial densities of 300 to 400 kg·m<sup>-3</sup> under various sintering times and temperatures. The neural network framework was readjusted and recalculated based on the newly supplemented experimental data.** The questions you raised have been answered in detail; the author's response is marked in blue, and the changes made to the original manuscript are marked in red. The comments and corresponding Responses are as follows:

## Summary

This manuscript presents methods, datasets, and results from a laboratory experiment related to the shear strength of compressed snow cylinders, where snow samples were obtained from an artificially created snowpack. The findings of this study could have significance for cold regions structural engineering applications, where infrastructure is built from compressed snow, and therefore stability of said infrastructure is highly dependent upon shear and normal strength of various snowpack types. Methods from the study include both an empirical approach involving laboratory testing, as well as a modeling approach, using a neural prediction network. Results of the two approaches include an observational dataset, as well as simulated model output, respectively.

The model was calibrated and validated via partitioning of the empirically derived data.

Four parameters were varied and tested in different combinations, using an applied horizontal shear force held constant for each variation of the other parameters. The varied parameters included initial compaction density, applied normal force, snow crystal sintering time, and sintering temperature. Internal friction angle and cohesion of the various samples were calculated using a previously established algorithm from the

30 literature.

The approach and results of this study are interesting and a valuable contribution to snow physics and mechanics, although the overall novelty of this experiment is limited. If the methods presented here can be replicated in future experiments, results from multiple studies could eventually provide a statistically significant body of evidence for  
35 establishing numerical thresholds for these snow shear strength parameters. Such thresholds would be valuable for practical use in snow engineering.

**Comment R2.1 (Overall):** Shear Stress vs Shear Strength: The authors use these words  
40 somewhat interchangeably; however, these are not really the same thing. Conceptually related, but distinct, shear stress is the internal force per unit area acting within a material due to external loads, while strength is the maximum stress said material can withstand before failure (plastic deformation). For this study, stress is the demand placed on each snow sample, while strength is the capacity of each sample. A material  
45 fails when the applied stress equals or exceeds its strength. This is commonly a grey area within the field of snow mechanics, because shear stress is a quantifiable variable with established units of measurement, while shear strength is more nebulous. Previous studies offer approaches for defining snow strength, but it is overall still more of a concept than it is a specific quantity. While sometimes perplexing, defining snow  
50 strength is still an open field of research with much opportunity for creativity.

**Response:** Thank you very much for your valuable comment. The author has corrected the instances where shear stress and shear strength were used interchangeably in the original manuscript:

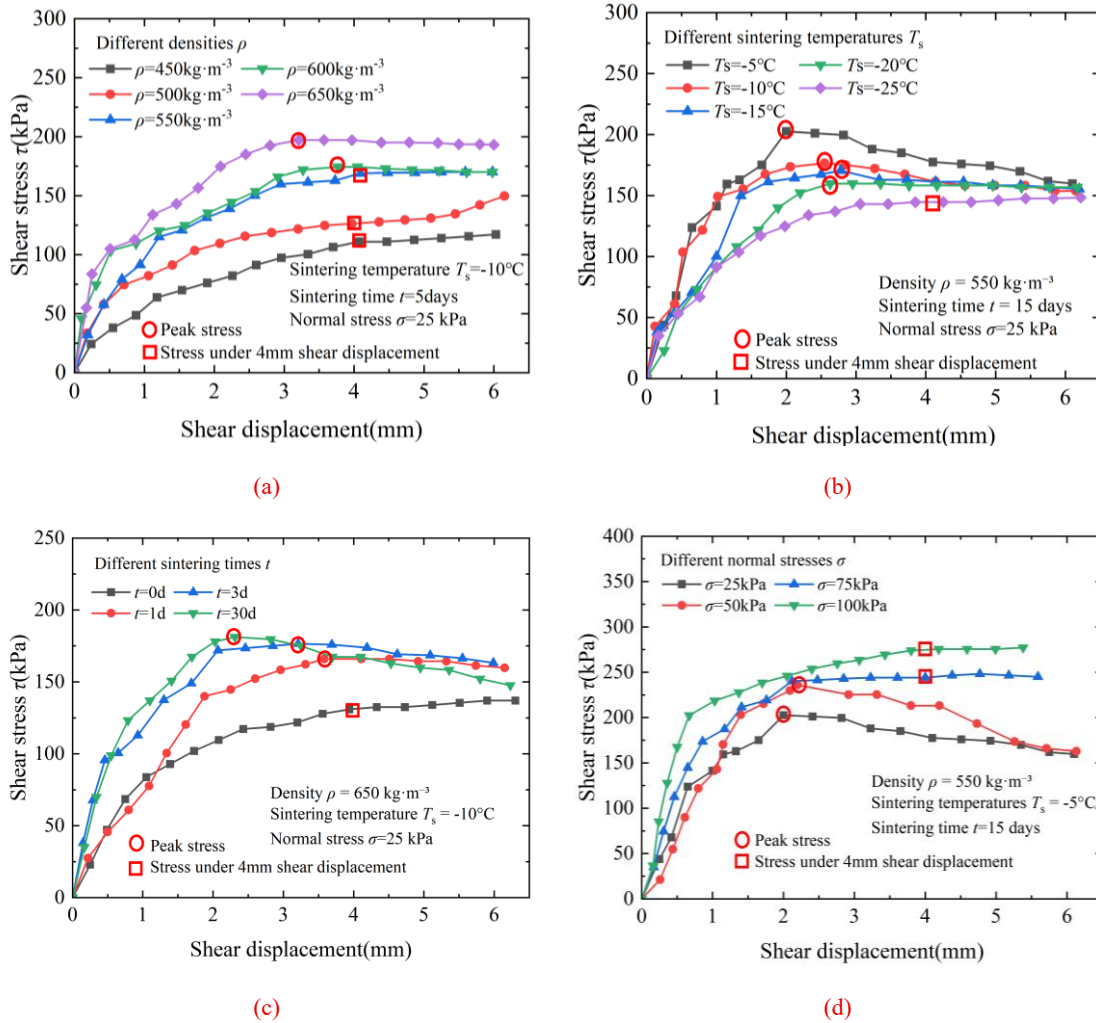


Figure 6: Shear stress–displacement curves under different test conditions ((a) Different densities; (b) Different sintering temperatures; (c) Different sintering times; (d) Different normal stresses).

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**Comment R2.2 (Overall):**

Abstract: Add a little more context (a couple sentences here) and briefly describe the conditions of the experiment. It would be easier to understand the summary of results and what the paper is about, with a simple description of the experiment set up, i.e., “experiments were conducted in a cold lab with environmental controls, using an instrument that does....” Which parameters were measured vs. calculated vs. modeled? Specify which parameters are the “essential strength parameters”.

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**Response:** Thank you for your comment. The abstract has been updated accordingly:

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**Abstract.** .....Direct shear tests were conducted on natural snow of lower density and artificial snow of higher density in a cold laboratory at  $-10^{\circ}\text{C}$ . A total of 112 test

conditions were examined to investigate the effects of initial density, sintering time, and sintering temperature on strength parameters under normal stresses below 100 kPa..... A Genetic Algorithm-Back Propagation (GA-BP) neural network was employed to develop a predictive model for shear strength using density, sintering time, sintering temperature, and normal stress as inputs, providing benchmark values for cohesion and internal friction angle under various conditions.

**Comment R2.3 (Overall):**

Introduction: I don't fully agree with the first part of the last paragraph in this section. I'm not sure that most previous studies within the snow engineering field of research are, in fact, focused on low density snow. I'd say the opposite is true. Most engineering related snow research actually does focus on compacted/altered snow, while avalanche research typically explores unaltered/natural, in-situ snowpacks. Either way, citations of studies on low density snow strength for snow engineering purposes should be provided. Or consider removing this section.

**Response:** Thank you for your comment. The author has added experiments on low-density snow in the range of 300 to 400 kg·m<sup>-3</sup>. Additionally, the wording in that section of the introduction has been revised accordingly:

In previous research, studies on snow avalanches have primarily focused on low-density natural snow (McClung, 1977; Schweizer, 1998), whereas engineering investigations have concentrated on compacted or artificially modified snow (Sun et al., 2021; White and McCallum, 2020; White, 2023). Although the shear strength of snow has been extensively examined, few studies have quantitatively investigated and discussed the key strength parameters essential for engineering evaluation, namely cohesion and the internal friction angle. On this basis, the present study conducted direct shear tests on natural snow with densities ranging from 300 to 400 kg·m<sup>-3</sup> and on artificial snow with densities ranging from 450 to 650 kg·m<sup>-3</sup>.

**Comment R2.4 (Overall):**

The novelty of this paper is not that it explores compacted snow. This study still has value in terms of contributing quantifiable results that could support (or not support) conclusions made by related studies. The results of this study could also be used in the future for establishing thresholds for certain snow parameters for engineering applications. The value is more practical than novel, which is fine.

**Response:** Thanks!

**Comment R2.5 (Overall):**

Neural network and prediction modeling: The agreement between the measured data and the modeled data from the neural network looks a little too good. The level of validation is sky high. I'm wondering if the model is overfit, considering 80% of the empirical dataset was used for calibration. Also, I'm not a neural network expert by any means, but isn't this a ton of computation power for predicting only four variables? I still think having a prediction model for these parameters is very valuable, but this looks like over-fitting to me.

**Response:** These questions will be addressed from the following perspectives:

(1) Selection of the dataset:

In the original manuscript, each condition in Table 1 represents a combination of variables, providing strength parameters (including shear strength values under four normal stresses). In machine learning, to enhance the generalization ability of the neural network, the shear strength values themselves were used as the dataset for network learning, rather than the strength parameters. In addition, the authors have supplemented experimental data for the density range of 300–400 kg·m<sup>-3</sup> under various combinations of sintering time and temperature, and recalculated using the neural network. Currently, the neural network includes experimental data under 112 different normal stress conditions, totalling 448 data points. This fully meets the computational requirements for a four-variable neural network.

(2) Issue of model overfitting:

We understand the reviewer's concern about the risk of overfitting in neural networks.

125 The following explanation is provided from two aspects: network architecture and  
predictive performance.

130 *Network architecture:* After supplementing the experimental data, the authors also  
modified the dataset split. 70 % of the data were used for training, 15 % for validation  
(to monitor overfitting), and 15 % for testing. This split ratio is a common practice in  
machine learning. It ensures that the training set is sufficiently large to learn the data  
patterns, while the test set is large enough to evaluate generalization ability. Table 1  
shows the dataset splits and network architectures used by other researchers for BP  
neural networks. After revision, the dataset split of the neural network in this study  
matches those in other studies. Regarding the number of neurons, the authors again  
135 considered the risk of overfitting. The hidden layer was changed from two layers to one  
layer, with 10 neurons. This prevents the network architecture from being too complex  
and causing overfitting. For a regression task with only four input variables, the current  
model has a network structure that is as simple as possible, reducing the risk of  
overfitting from the architectural design.

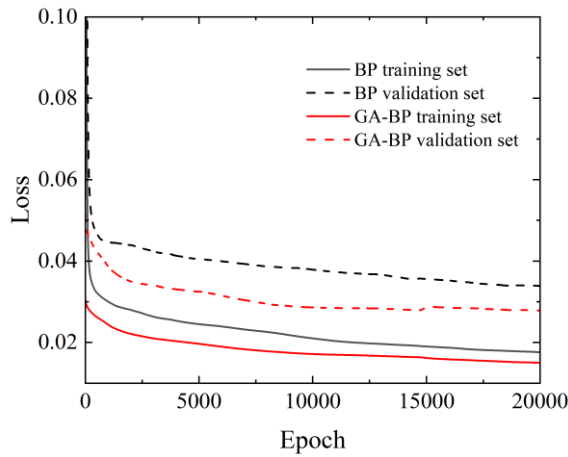
140 **Table 1** Data set partitions and network architectures for BP neural networks by other researchers.

Researchers	Data volume	Data split	Network architecture (input layer - hidden layers - output layer)
Hou (2024)	107	70% for the training set; 15% for the validation set; 15% for the test set	5-10-2
Feng (2024)	200	70% for the training set; 15% for the validation set; 15% for the test set	6-16-2
Liang (2024)	81	71 sets as the training set, 10 sets as the test set	3-5-3

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*Predictive performance:* The performance difference between the training set and the test set is a key indicator of overfitting. A severely overfitted neural network typically shows very high accuracy on the training set but sharply lower accuracy on the test and validation sets. Also, during training, the training loss is low while the validation loss suddenly increases. Figure 1 shows the epoch-loss curve of the model. It indicates that as training proceeds, the validation loss decreases steadily and consistently. Furthermore, the comparison results in Table 3 of this study show that although the test set performance is slightly inferior to that of the training set, the decrease is limited, and the absolute accuracy on the test set remains high. This small difference is a normal generalization error, not a loss of predictive ability caused by overfitting.



**Figure 1: Epoch-loss curve**

**Table 3 Performance evaluation metrics for training and test sets.**

	$R^2$	$RMSE$	$MAE$
Training set ( <i>BP</i> )	0.986	9.65	7.15
Training set ( <i>GA-BP</i> )	0.987	9.59	6.98
Improvement ratio (%)	0.1	0.62	2.4
Test set ( <i>BP</i> )	0.958	14.76	10.83
Test set ( <i>GA-BP</i> )	0.967	13.13	9.14
Improvement ratio (%)	0.94	11.04	15.6

155 From the above analysis, the neural network model in this study performs stably on  
both the validation set and the test set. The performance difference is within an  
acceptable range. Moreover, the model's behavior is consistent with the physical trends  
observed in the experiments (see Figs. 21–22 in the manuscript). Therefore, the authors  
believe that after revision, the current model has sufficient accuracy and generalization  
160 ability to support the conclusions of this paper. At the very least, there is no serious  
overfitting problem.

Corresponding content has been added to the original manuscript.

#### **4 Prediction Using *GA-BP* Neural Network**

165 As demonstrated in Section 3, the effects of various influencing factors on shear  
strength exhibit certain interactions and nonlinear relationships. Such behaviors are  
difficult to accurately capture using traditional function fitting methods. In contrast,  
neural networks possess more powerful capabilities in processing nonlinear data. To  
quantitatively characterize the specific influence trends of these factors, this section  
170 utilizes a genetic algorithm (*GA*) to optimize a back propagation (*BP*) neural network.  
Based on experimental data, a predictive model was developed with initial density,  
sintering time, sintering temperature, and normal stress as input variables, and shear  
strength as the output variable. The model aims to explore the underlying relationships  
among these parameters.

175 .....

##### **4.1.1 Data Collection and Preprocessing**

A total of 448 experimental data points were collected, with 70% randomly selected as  
the training set, 15% as the validation set, and the remaining 15% used for testing.....

180 .....

#### 4.2.2 Neural Network Prediction Results

After training the neural network model, 15% of the total dataset (67 samples), which were not part of the training set, were randomly selected as the test set. The accuracy of the trained neural network was then evaluated by comparing the predicted results with the actual values.....

#### References:

Hou, L., Zhang, Q., and Du, Y.: Width estimation of hidden cracks in tunnel lining based on time-frequency analysis of GPR data and back propagation neural network optimized by genetic algorithm, *Automat. Constr.*, 162, 105394, <https://doi.org/10.1016/j.autcon.2024.105394>, 2024.

Feng, Q., Xie, X., Wang, P., et al.: Prediction of durability of reinforced concrete based on hybrid-Bp neural network, *Constr. Build. Mater.*, 425, 136091, <https://doi.org/10.1016/j.conbuildmat.2024.136091>, 2024.

Liang, J., Du, X., Fang, H., et al.: Intelligent prediction model of a polymer fracture grouting effect based on a genetic algorithm-optimized back propagation neural network, *Tunn. Undergr. Space Technol.*, 148, 105781, <https://doi.org/10.1016/j.tust.2024.105781>, 2024.

#### Comment R2.6 (Overall):

Discussion Section: This section needs a lot of work and major revision and improvements. It seems like the authors ran out of steam by the time they got to this part of the manuscript. Discussions are often the most difficult section to craft, yet the most important part of most papers. Organizing this section by snow parameter seems like a good way to start, but there are actually zero conclusions drawn from the results of the study. Each parameter listed in this section is accompanied only by some literature citations. The authors need to clearly communicate conclusions drawn from conducting the experiment, supported by the study outcomes. The overall messages that the authors wish for the readers to take away need to be stated, using specific examples from the results section as evidence for conclusions drawn. Refer to the results

presented, including the empirical measurements, results from calculations, figures etc., and the modeled output. The conclusion also needs more work and should be tied back into how this study is valuable for snow structural engineering.

215 **Response:** The discussion and conclusion sections have been rewritten:

### **4.3 Discussion**

#### **4.3.1 Physical mechanisms governing the evolution of direct shear strength parameters**

220 Initial density is the most important factor affecting the direct shear strength and strength parameters of compacted snow. An increase in density leads to more contact points between snow particles per unit volume and a denser internal structure (Butkovich, 1958; Mellor, 1977). This enhances interparticle bonding and frictional interlocking. As shown in Fig. 11, when the initial density increased from 300 to 650  $\text{kg}\cdot\text{m}^{-3}$ , both cohesion and internal friction angle exhibited a significant increasing trend.

225 Under the condition of sintering at  $-10\text{ }^{\circ}\text{C}$  for 5 days, cohesion increased from 25.73 to 161.85 kPa, and the internal friction angle increased from 18.65 to 60.98 $^{\circ}$ .

With increasing sintering time, the strength of compacted snow is jointly determined by sublimation and the formation of hydrogen bonds between snow particles (i.e., sintering). In the early stage of sintering, hydrogen bonds between snow particles form rapidly, while the density reduction caused by sublimation is not yet pronounced. During this stage, strength increases quickly. Afterwards, the sintering process stabilizes, and density continues to decrease. Under the combined effect of both processes, shear strength fluctuates slightly but remains relatively stable. As sintering time further increases, sublimation becomes the dominant factor, leading to a continuous decrease in strength.

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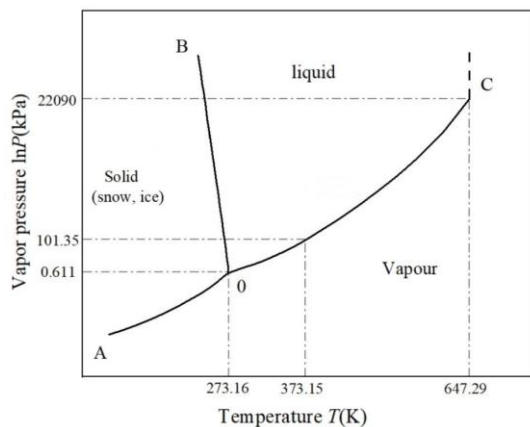
During sintering, the protrusions on snow particle surfaces sublime preferentially, making the particle shapes more regular. This reduces the surface roughness of snow particles, resulting in a continuous decrease in the internal friction angle. Cohesion follows a trend similar to that of strength: it first increases and then decreases gradually.

240 As shown in Fig. 14, taking a density of 550  $\text{kg}\cdot\text{m}^{-3}$  and a temperature of  $-10\text{ }^{\circ}\text{C}$  as an example, with sintering time increasing to 60 days, cohesion first increased from 53.54

to 141.85 kPa and then decreased to 131.99 kPa. Meanwhile, the internal friction angle decreased from 52.78 to 38.58°.

245 An increase in sintering temperature enhances the Brownian motion of water vapor, facilitating the formation of hydrogen bonds between snow particles (Abele, 1967, 1990; Colbeck, 1983a). A higher degree of sintering strengthens interparticle bonding and makes particle surfaces more regular. As can be seen from Fig. 16, when the sintering temperature increased from -25 to -5 °C, cohesion increased significantly (for the condition of density 550 kg·m<sup>-3</sup> and sintering for 16 days, cohesion increased from 115.4 to 183.72 kPa), whereas the internal friction angle decreased from 48.69 to 41.74°.

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**Figure 24: Phase diagram of water (A denotes the sublimation line, B denotes the melting line, and C denotes the evaporation line).**

### 4.3.2 Comparison with existing studies

255 This study systematically investigated the variation trends of strength and strength parameters of compacted snow by considering initial density, sintering time, and sintering temperature. The effects of initial density and sintering temperature are consistent with previous findings (Butkovich, 1958; Ballard et al., 1965; Perla and Beck, 1982; Schweizer, 1998). Regarding the effect of sintering time, similar conclusions

260 have been obtained from both field and laboratory studies (Jellinek, 1959; Zhuang, 2019; Fu, 2020; Yang, 2024). In contrast, Abele (1990) reported that the sintering strength of

snow kept increasing without a decreasing trend. However, that study did not clearly describe the experimental details (e.g., ambient humidity and the sealing conditions of the specimens). Therefore, more refined experiments are needed in the future to further investigate the strength variation trends of compacted snow.

### 4.3.3 Highlights and limitations of this study

Through laboratory experiments and a neural network model, this study obtained baseline values of direct shear strength parameters for compacted snow under the following conditions: density 300 to 650 kg·m<sup>-3</sup>, sintering temperature -5 to -25 °C, sintering time 0 to 60 days, and normal stress 25 to 100 kPa. Engineers can use these baseline values to perform deformation, bearing capacity, and stability calculations for snow facilities in polar cold regions. When snow type or environmental conditions change, new strength parameters can be obtained through laboratory tests. A quantitative relationship can then be established between the new indices and those from this study, allowing the baseline values to be corrected.

This study only considered initial density, sintering temperature, sintering time, and normal stress (25 to 100 kPa), with a loading rate of 0.8 mm·min<sup>-1</sup>. How strength parameters of compacted snow change under other internal and external factors remains to be investigated in future work. Internal factors include snow type, water content, and particle size. External factors include ambient humidity, sealing conditions, loading rate, and normal stress.

### References:

- Abele, G. and Frankenstein, G. E.: Snow and ice properties as related to roads and runways in Antarctica, US Army CRREL Technical Report 190, Cold Regions Research and Engineering Laboratory, Hanover, ASIN B0007F4F4A, 1967.
- Abele, G.: Snow roads and runways, CRREL Monograph 90-2, US Army Cold Regions Research and Engineering Laboratory, Hanover, 1990.
- Butkovich, T. R.: Strength studies of high-density snows, Eos Trans. AGU, 39, 305–312, <https://doi.org/10.1029/TR039i002p00305>, 1958.

Colbeck, S. C.: Theory of metamorphism of dry snow, *J. Geophys. Res. Oceans*, 88, 5475–5482, <https://doi.org/10.1029/JC088iC09p05475>, 1983a.

295 Fu, X.: Test study on seasonal snow thermal properties and mechanical properties in Northeast China, M.S. Thesis, Northeast Agricultural University, <https://doi.org/10.27010/d.cnki.gdbnu.2020.000222>, 2020.

Jellinek, H.: Compressive strength properties of snow, *J. Glaciol.*, 3, 345–354, <https://doi.org/10.3189/S0022143000017019>, 1959.

300 Mellor, M.: Engineering properties of snow, *J. Glaciol.*, 19, 15–66, <https://doi.org/10.3189/S002214300002921X>, 1977.

Perla, R., Beck, T. M. H., and Cheng, T. T.: The shear strength index of alpine snow, *Cold Reg. Sci. Technol.*, 6, 11–20, [https://doi.org/10.1016/0165-232X\(82\)90040-4](https://doi.org/10.1016/0165-232X(82)90040-4), 1982.

305 Schweizer, J.: Laboratory experiments on shear failure of snow, *Ann. Glaciol.*, 26, 97–102, <https://doi.org/10.3189/1998AoG26-1-97-102>, 1998.

Yang, M.: Analysis on Mechanical Characteristics and Influencing Factors of Compacted Snow in Northeast China, Master's thesis, Northeast Agricultural University, <https://doi.org/10.27010/d.cnki.gdbnu.2024.000351>, 2024.

310 Zhuang, F.: Experimental Study on Snow Hardness and Its Testing Technology, M.S. Thesis, Dalian University of Technology, <https://doi.org/10.26991/d.cnki.gdllu.2019.000727>, 2019.

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## 315 **5 Conclusions**

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(4) Based on the GA-BP neural network, this study provides benchmark values of shear strength parameters for compacted snow under different densities, sintering times, and sintering temperatures, offering quantitative references for the design and construction of snow structures in engineering practice. In future work, these benchmark values can  
320 be adapted and extended for different engineering environments and compaction

techniques to support parameter selection and performance evaluation of snow engineering structures in various application scenarios.

### References:

- 325 Abele, G. and Frankenstein, G. E.: Snow and ice properties as related to roads and runways in Antarctica, US Army CRREL Technical Report 190, Cold Regions Research and Engineering Laboratory, Hanover, ASIN B0007F4F4A, 1967.
- Abele, G.: Snow roads and runways, CRREL Monograph 90-2, US Army Cold Regions Research and Engineering Laboratory, Hanover, 1990.
- 330 Butkovich, T. R.: Strength studies of high-density snows, *Eos Trans. AGU*, 39, 305–312, <https://doi.org/10.1029/TR039i002p00305>, 1958.
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- Jellinek, H.: Compressive strength properties of snow, *J. Glaciol.*, 3, 345–354, <https://doi.org/10.3189/S0022143000017019>, 1959.
- Mellor, M.: Engineering properties of snow, *J. Glaciol.*, 19, 15–66, <https://doi.org/10.3189/S002214300002921X>, 1977.
- 340 Perla, R., Beck, T. M. H., and Cheng, T. T.: The shear strength index of alpine snow, *Cold Reg. Sci. Technol.*, 6, 11–20, [https://doi.org/10.1016/0165-232X\(82\)90040-4](https://doi.org/10.1016/0165-232X(82)90040-4), 1982.
- Schweizer, J.: Laboratory experiments on shear failure of snow, *Ann. Glaciol.*, 26, 97–102, <https://doi.org/10.3189/1998AoG26-1-97-102>, 1998.
- 345 Yang, M.: Analysis on Mechanical Characteristics and Influencing Factors of Compacted Snow in Northeast China, Master's thesis, Northeast Agricultural University, <https://doi.org/10.27010/d.cnki.gdbnu.2024.000351>, 2024.

Zhuang, F.: Experimental Study on Snow Hardness and Its Testing Technology, M.S.  
350 Thesis, Dalian University of Technology,  
<https://doi.org/10.26991/d.cnki.gdllu.2019.000727>, 2019.

### Specific line-number comments

L30: Deeper snow layers, especially at the base of the snowpack, do not always get  
355 stronger over time from compaction of overlying snow layers. Changes in the  
temperature gradient from top to bottom of the snow profile often cause faceting and  
weakening of the basal layer crystal bonds. Qualify this sentence by specifying under  
what conditions at a snow construction site would base layers of the snowpack be  
strongly bonded and not faceted.

360 **Response:** Thank you for your comment. The author has removed the inaccurate  
statements from the original manuscript and revised the sentences:

In engineering, snow is typically compacted and sintered to enhance the strength of the  
snow layer.

365 L35: which snow layer? Or referring to snow in general?

**Response:** This refers generally to snow; the manuscript has already been revised.

L46: awkward wording, "shear rate strongly influences snow strength and failure  
modes....."

370 **Response:** Thanks. Revisions have been made:

Shear rate strongly influences snow strength and failure modes.

L47: awkward wording, do you mean "strength initially increases, then subsequently  
decreases rapidly with the transition from ductile to brittle"?

375 **Response:** Thanks. Revisions have been made:

Shear strength initially increases, and subsequently decreases rapidly with the transition  
from ductile to brittle (McClung, 1977; De Montmollin, 1982; Puzrin et al., 2019).

L50: I think I understand the concept here, but the sentence needs rewording for clarity

380 **Response:** Thanks. Revisions have been made:

De Montmollin (1982) investigated the effect of shear rate on snow failure, classifying failure modes and demonstrating that, within the medium to high shear rate range, shear strength was shown to decrease as shear rate increases. Residual stress after brittle failure was also shown to decrease with increasing shear rate.

385

L56: Name the three instruments described and invented in 2016, 2010, and 2013.

**Response:** All three instruments were developed independently by the researchers, and their names are not mentioned in the original literature. The author has provided  
390 additional notes in the manuscript describing the operating conditions of these three instruments to clarify their functions:

To overcome this limitation, Barbero (2016) developed an apparatus for in-situ direct shear tests that integrates the functions of a sampler and a shear box, enabling the collection of nearly undisturbed snow specimens and allowing precise control and  
395 monitoring of normal and shear stresses via a pneumatic system. Reiweger (2010) designed a laboratory loading apparatus capable of tilting snow samples to simulate slope angles; it applies incremental weights to mimic snowfall loading and can be combined with particle image velocimetry for local strain analysis and acoustic emission monitoring to track damage processes. Podolskiy (2013) developed a portable  
400 shear loading apparatus that permits shearing of a predefined weak interface; by sintering two snow blocks and shearing along the bonded interface, the device can be used to assess the contribution of sintering to snow strength.

L61: What is a "variation pattern"? This seems vague to me. Are you referring to snow  
405 strength spatial variability across a landscape? Or snow strength variations temporally over a winter season or variations in the snowpack profile?

**Response:** The authors intended to convey in the original text that the trends in snowfall intensity vary with different influencing factors; this has been revised in the manuscript:

410 While previous research has primarily examined the variation trends of shear strength in compacted snow under various influencing factors.

L65- 69: The specific study objectives need to be clarified here.

**Response:** Revisions have been made:

415 A total of 112 test conditions were designed, considering variations in initial density, sintering time, and sintering temperature, and direct shear tests were conducted on compacted snow. Based on the shear stress–displacement curves, the shear strength was defined as the peak shear stress for strain-softening curves and as the shear stress at a shear displacement of 4 mm for strain-hardening curves. The cohesion  $c$  and internal  
420 friction angle  $\varphi$  were then determined according to the Mohr–Coulomb linear criterion, and their values and variation trends under the influence of different factors were analyzed. A Genetic Algorithm-Back Propagation (GA-BP) neural network was used to develop a predictive model for strength parameters under multi-variable coupling conditions, providing benchmark values for cohesion  $c$  and internal friction angle  $\varphi$   
425 across various combinations of influencing factors.

L75- 84: Clarify which of these steps described in the methods are for the initial snow making process and which are the subsequent sample collection and preparation steps.

430 **Response:** The title of Section 2.1 has been changed to *Snow Production and Sample Preparation*

L80: Where was this done? In a cold lab?

435 **Response:** The snowmaking process takes place outdoors, while the remaining steps

(sample preparation, sintering, and shearing) are all performed in a temperature-controlled freezer. The manuscript has been revised.

L82: the snow crystals were plate-like, not the snow samples

440 **Response:** Thanks. Revisions have been made.

L89: were the uniform snowflakes spread inside the ring before sealing with the membrane? It sounds like the opposite, i.e. the snowflakes were added after applying  
445 the membrane.

**Response:** When a snow specimen is exposed to the external environment, the surface in contact with the air sublimates rapidly. In practical engineering, the snow we test is inside the snow layer and does not directly contact the air. This experiment simulated real conditions: during sintering, the ring mold was completely surrounded by snow,  
450 but the upper and lower surfaces of the specimen were also covered with snow, which easily led to hydrogen bonding and cementation between the specimen surface and the external snow. When preparing for the shear test, the specimen had to be separated from the surrounding snow, which inevitably disturbed the specimen. Therefore, a thin film was applied to the specimen to solve this problem. During sintering, gas exchange  
455 between the specimen and the environment remained possible, but cementation with external snow was prevented.

Based on the above response, the authors revise and supplement the original content of the manuscript:

**Sintering:** to simulate the natural sintering environment, a sealing membrane was first  
460 placed over the compacted sample (still within the ring formwork). Uniform snowflakes were then spread around the sample and over the membrane to replicate the conditions inside snow layer. The surrounding snowflakes prevented rapid sublimation from exposed surfaces, while the membrane isolated the sample from the snow placed above it, thereby avoiding sintering bonding between the sample and the external snow. The

465 entire assembly was then placed in a test chamber and sintered at the specified  
temperature for the designated duration. Figure 1(b) shows samples covered with  
membranes, and Figure 1(c) shows snowflakes deposited on the samples and the  
membrane.



470 **Figure 1: Sample preparation process ((a) Compacted specimen; (b) Samples covered with membranes; (c) Sprinkling snowflakes).**

L96: I think you mean "snow sample shearing process, using the equipment", not "equipment shearing process".

**Response:** Thanks. Revisions have been made.

475

L100: This is confusing. How would one pre-define the shearing plane? The samples will shear where the two boxes meet, correct?

**Response:** In the direct shear tests conducted in this study, the shear plane was created by the horizontal displacement between the upper and lower shear blocks. The original sentence was intended to emphasize that no artificial weak planes were introduced during specimen preparation. To avoid ambiguity, the manuscript has been revised:

480 A dynamometer is mounted on the upper box. The shear plane is defined by the interface between the upper and lower shear boxes, and shear failure develops naturally as the lower box moves relative to the upper box.

485

2.2 and 2.3: Be more consistent and accurate when referring to shear force (force per unit area) vs. shear rate (displacement over time). Also be consistent and clear on the difference between the applied shear stress vs. how this study reasonably decided to

define shear strength (amount of applied stress required for plastic deformation, or  
490 measured shear stress at 4mm displacement when plastic deformation does not occur).

**Response:** Thanks. The usage of “shear stress” and “shear strength” has been  
standardized throughout the manuscript.

Figure 4: The x- axis label needs to include the units. 图 4: x 轴标签需要包含单位。

495 **Response:** Thank you for pointing that out. The original image has been corrected.

L106- 108: This sentence is very confusing. What is increasing initially and then shows  
a decreasing trend? Strength or strain? Also the relationship here is stated as shear strain  
rate vs. strength, but the axes in figure 4 are labeled as strain rate vs. stress. Be consistent.

500

**Response:** Thank you for your comment. The author has revised the sentence in the  
original text to avoid any ambiguity. Additionally, the vertical axis label in Figure 4 has  
been confirmed as *Shear strength*, and the horizontal axis label is *Shear strain rate*.

Fig. 4 (redrawn from Puzrin et al., 2019) shows that as the shear strain rate increases,  
505 the shear strength of snow first increases and then decreases, while the strength  
parameters also change accordingly.

L115: Clarify what is meant by "patterns in failure modes and strength variations".

**Response:** Thank you for your comment. *Failure* refers to the two types of shear stress-  
510 displacement curves (strain hardening and strain softening); *strength variation* refers to  
changes in the snow's shear strength in response to external factors. To avoid ambiguity,  
we have revised the manuscript as follows:

Moreover, the transition between these two failure modes exhibited a clear trend. The  
variation of shear strength with external factors followed a similarly well-defined trend.

515

L127: Is this really data processing or data collection?

**Response:** In the manuscript, *Data Processing* has been changed to *Data Collection  
and Processing*.

520 L135: provide a citation for the  $400\text{kg}/\text{m}^3$  threshold or where does this quantity come from? This sentence also needs to be written more clearly. What is meant by interparticle friction impeding density? Do you mean that  $700\text{kg}/\text{m}^3$  is as dense as snow can get before turning to glacier ice or firn? Refer to Cuffey and Patterson, 2010, for density ranges for snow, firn, and ice.

525 **Response:** Thank you for your comment. Regarding the source of the density threshold between  $400$  and  $700\text{ kg}\cdot\text{m}^{-3}$  and the expression “interparticle friction hinders density increase”, we provide the following clarification and revision.

(1) Source of the  $400\text{ kg}\cdot\text{m}^{-3}$  threshold:

530 This threshold is mainly based on pre-test observations in this study. For artificial snow, when the density is below  $400\text{ kg}\cdot\text{m}^{-3}$ , the internal structure of the specimen is loose and the pores are large. It is difficult to form an intact and stable specimen. When the density reaches  $450\text{ kg}\cdot\text{m}^{-3}$ , the specimen already exhibits good formability after compaction and can meet the requirements for subsequent sintering and shear tests. Therefore, this study selected  $450\text{ kg}\cdot\text{m}^{-3}$  as the lower limit of density for artificial snow.

535 (2) Regarding the  $700\text{ kg}\cdot\text{m}^{-3}$  threshold and the expression “interparticle friction”:

The original expression “interparticle friction hinders density increase” was not sufficiently accurate. What we intended to convey is that during mechanical compaction, when the density approaches  $700\text{ kg}\cdot\text{m}^{-3}$ , the contact area between snow particles increases significantly, and the interparticle frictional resistance rises sharply. This makes further compaction extremely difficult. Under the laboratory conditions of this study,  $650\text{ kg}\cdot\text{m}^{-3}$  is the maximum density that can be achieved by manual compaction using tools. In nature, this density range corresponds to the transition from firn to ice (Cuffey & Paterson, 2010). Therefore, this study selected a density range of  $450$ – $650\text{ kg}\cdot\text{m}^{-3}$ .

545 We have revised the wording in the main text accordingly, and added a description of natural snow specimens with densities ranging from  $300$  to  $400\text{ kg}\cdot\text{m}^{-3}$ .

Naturally deposited snow requires compaction prior to utilization as an engineering

material. Preliminary tests indicated that for machine-made snow with a natural density  
550 of approximately  $300 \text{ kg}\cdot\text{m}^{-3}$ , when the compacted density is below  $400 \text{ kg}\cdot\text{m}^{-3}$ , the  
specimen remains loosely structured with large internal pores. Consequently, it is  
difficult to form a stable and intact specimen. When the density reaches  $450 \text{ kg}\cdot\text{m}^{-3}$ , the  
specimen exhibits good formability and structural integrity after compaction, meeting  
the requirements for subsequent sintering and shear testing. Under mechanical  
555 compaction, as the density approaches approximately  $700 \text{ kg}\cdot\text{m}^{-3}$ , the interparticle  
contact area increases substantially, leading to a sharp rise in frictional resistance, which  
renders further densification extremely difficult. Under the laboratory conditions of this  
study,  $650 \text{ kg}\cdot\text{m}^{-3}$  was the maximum density achievable through manual compaction  
using tools. Similarly, for natural snow with an initial density of approximately  
560  $200 \text{ kg}\cdot\text{m}^{-3}$ , a stable specimen could only be formed when compacted to a density of  
 $300 \text{ kg}\cdot\text{m}^{-3}$ . Accordingly, in this study, natural snow was used to prepare specimens  
with densities ranging from  $300$  to  $400 \text{ kg}\cdot\text{m}^{-3}$ , while machine-made snow was used to  
prepare specimens with densities ranging from  $450$  to  $650 \text{ kg}\cdot\text{m}^{-3}$ .

565 Table 1: The Serial # column could use a description of why the various experiment  
trials were labeled D- 1 vs t- 1 vs T- 1, etc. It's somewhat obvious, but only after reading  
well past the table and then referring back to it. The way multiple trials are listed on  
one line totally makes sense and is easy to understand, but I don't get the numbering in  
the first column, i.e., the first line (D- 1) is really tests 1 through 20, and the second line  
570 (D- 2) is for tests 21 through 40; the fourth line is for tests 61- 72, I think. Lastly, it was  
stated earlier that there were 69 test conditions, but this table shows many more  
parameter combinations and tests than that.

**Response:** Table 1 has been revised and updated with new operating conditions, and a  
note has been added to clarify that each operating condition consists of four normal  
575 stresses, in order to avoid ambiguity:

The effects of initial density  $\rho$ , sintering time  $t$ , and sintering temperature  $T_s$  were  
systematically examined through 112 test conditions, as detailed in Table 1. Each test  
condition includes the shear strength under four normal stresses.

**Table 1** Test conditions.

Serial number	$\rho$ (kg·m <sup>-3</sup> )	$t$ (days)	$T_s$ (°C)	Other variables
D-1	300,350,400,450,500,550,600,650	5	-5	$\sigma=25,50,75,100$ kPa
D-2	300,350,400,450,500,550,600,650	5	-10	$\sigma=25,50,75,100$ kPa
D-3	300,350,400,450,500,550,600,650	5	-20	$\sigma=25,50,75,100$ kPa
t-1	300	0,1,3,5,10,15,20,30,60	-10	$\sigma=25,50,75,100$ kPa
t-2	350	0,1,3,5,10,15,20,30,60	-10	$\sigma=25,50,75,100$ kPa
t-3	400	0,1,3,5,10,15,20,30,60	-10	$\sigma=25,50,75,100$ kPa
t-4	450	0,1,3,5,10,15,20,30,60	-10	$\sigma=25,50,75,100$ kPa
t-5	550	0,1,3,5,10,15,20,30,60	-10	$\sigma=25,50,75,100$ kPa
t-6	650	0,1,3,5,10,15,20,30,60	-10	$\sigma=25,50,75,100$ kPa
T-1	300	15	-5, -10, -15, -20, -25	$\sigma=25,50,75,100$ kPa
T-2	350	15	-5, -10, -15, -20, -25	$\sigma=25,50,75,100$ kPa
T-3	400	15	-5, -10, -15, -20, -25	$\sigma=25,50,75,100$ kPa
T-4	450	15	-5, -10, -15, -20, -25	$\sigma=25,50,75,100$ kPa
T-5	550	15	-5, -10, -15, -20, -25	$\sigma=25,50,75,100$ kPa
T-6	650	15	-5, -10, -15, -20, -25	$\sigma=25,50,75,100$ kPa
H-1	300	1,30	-5, -20	$\sigma=25,50,75,100$ kPa
H-2	350	1,30	-5, -20	$\sigma=25,50,75,100$ kPa
H-3	400	1,30	-5, -20	$\sigma=25,50,75,100$ kPa
H-4	550	1,30	-5, -20	$\sigma=25,50,75,100$ kPa

580

L144-145: This needs to be stated at the beginning of the paper, i.e. "In our study, we define shear strength as the peak shear stress right before plastic deformation or critical displacement", or a similar statement should be in the introduction and/or methods sections.

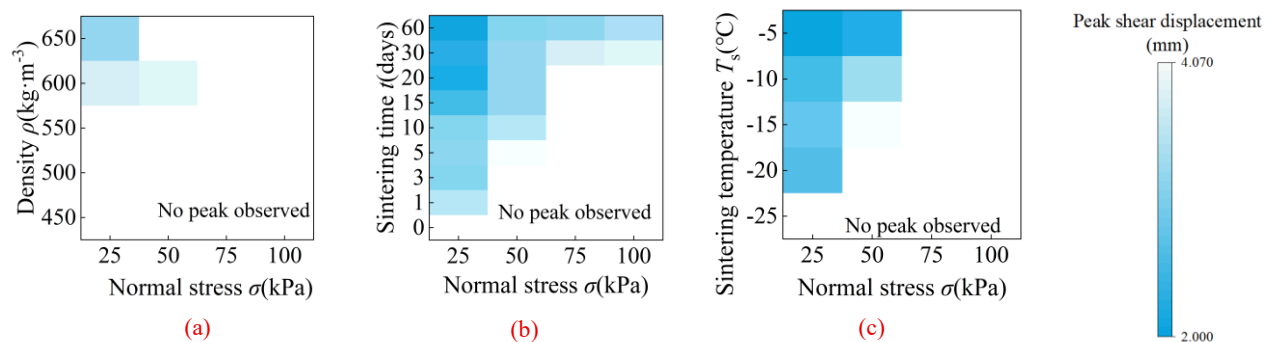
585

**Response:** The relevant content has been added to the introduction of the manuscript: Based on the shear stress–displacement curves, the shear strength was defined as the

peak shear stress for strain-softening curves and as the shear stress at a shear displacement of 4 mm for strain-hardening curves.

590 Figure 7: The idea of representing the shear stress - displacement curves in this alternative way seems creative and intuitive to me. I really like this figure. However, I wondering if I don't understand how to read it correctly. Maybe a sentence or two in the text on how to read this figure would help. Because I thought I got it, but to me, it looks like in graph (a), at 25kpa normal force, density of 650kg/m<sup>3</sup> , t = 5 days, Temp = -10 deg C, the peak shear displacement is roughly 2,000mm , but in graph (b) the same combination of parameters shows the peak shear displacement as more like 3,000mm .

**Response:** Thank you for your comment! The color scheme in the original figure was indeed inconsistent, so Figure 7 has been redrawn.



600 **Figure 7: Development trends of shear stress–displacement curves under varying influencing factors ((a) Different densities; (b) Different sintering times; (c) Different sintering temperatures).**

Equation (1) and the process of calculating internal friction angle and cohesion needs to be added in the methods section. One or two sentences in the methods should be fine.

605

L173: Which author are you referring to here? At first I thought this was in reference to the authors of the citations provided for equation (1), but then it says the "advance shear tests up to 350kpa" were done in the experiments from this paper? This is a whole new aspect/component of the experiment not described previously in the methods section.

610 This needs to be added as the first step, or one of the first steps, in the methods.

**Response:** Thank you for your comment. The two issues mentioned above have been addressed in the manuscript. We have added the calculation procedures for cohesion and internal friction angle to the experimental methods section, as well as the preliminary tests.

615 Numerous studies (McClung, 1977; Barbero, 2016; Perla, 1977; Fyffe, 2007; Chiaia, 2008; Gaume, 2014) have adopted the Mohr–Coulomb criterion as the failure criterion for snow. Preliminary tests were first conducted under normal stresses ranging from 25 to 350 kPa to identify the linear segment of the shear strength–normal stress envelope. Based on the results, the mean and standard deviation of shear strength were plotted for  
620 the three parallel specimens under each test condition. According to the Mohr–Coulomb linear criterion (Eq. (2)), the cohesion  $c$  and internal friction angle  $\varphi$  were then determined using the least squares method, and the error bars of  $c$  and  $\varphi$  were also plotted based on the fitting results.

$$\tau_f = c + \sigma \tan \varphi \quad (2)$$

625 where  $\tau_f$  represents the shear strength,  $\sigma$  represents the normal stress, and  $c$  and  $\varphi$  represent cohesion and internal friction angle, respectively.

L174: what is a "partial test"?

**Response:** This refers to preliminary experiments conducted under normal stresses  
630 ranging from 25 to 350 kPa; the manuscript has been revised to avoid any misleading statements.

Section 3.2.2: I enjoyed looking at the data and results in this section, but there is nothing that new here. It more or less just shows how snow crystal sintering over time  
635 increases bonding up to a certain point, but with continued aging of the snowpack, there is mass loss and bond weakening due to sublimation. This can be seen in the experiment's laboratory generated snowpack, as evidenced by the graphs in this section. Also, shows evidence to support that warmer temperatures lead to stronger bonding, which is well known. I suggest moving this section into an appendix. It's neat to look

640 at but makes the paper longer than necessary.

**Response:** Thank you for your comment. We have revised the content in Section 3.2.2 and moved some of it to the discussion section.

645 L249: define "back propagation".

**Response:** The definition of the BP neural network has been added in 4.1.2 *BP Neural Network Model*:

A back propagation (BP) neural network adjusts connection weights by propagating errors backward from the output layer to the input layer, and is commonly used for  
650 nonlinear function approximation.

In addition, Section 4.1.3, *GA-BP Neural Network Model*, provides a detailed description of the specific construction method for the GA-BP neural network.

Section 4.1 belongs in the methods.

655 **Response:** Revised to *4.1 Model Establishment Method*

L255: Where did the 276 points come from? This is the first its mentioned in the paper and might be the number of tests in Table 1? How do these relate to the 69 test conditions?

660 **Response:** Thank you for your comment. We have added additional notes regarding the operating conditions in Table 1.:

The effects of initial density  $\rho$ , sintering time  $t$ , and sintering temperature  $T_s$  were systematically examined through 112 test conditions, as detailed in Table 1. Each test condition includes the shear strength under four normal stresses, for a total of 448 sets  
665 of shear strength values.

Section 4.1.3 needs to be much expanded. This whole component of the study, the neural network, is not explained in any detail.

**Response:** It has been expanded to explain the specific steps involved in neural network

670 models:

#### 4.1.3 GA-BP Neural Network Model

To prevent the traditional BP algorithm from converging to local optima due to random initialization of weights, this paper adopts a genetic algorithm (GA) to optimize the initial weights and thresholds of the BP neural network. The construction procedure is as follows. First, the data are normalized. Then, actual values encoding is used to randomly generate an initial population. Each individual represents a candidate set of weights and biases. The fitness function is defined as the reciprocal of the mean square error (MSE) between the predicted shear strength and the actual value. A smaller error leads to a higher fitness. Through genetic operations (selection, crossover, and mutation), the population is iteratively optimized until a preset number of generations or a convergence criterion is reached. The individual with the highest fitness is selected as the optimal initial parameters. Subsequently, these parameters are used to train the BP network. Forward propagation computes the predicted values. The MSE loss is calculated. The error is back-propagated to update weights and thresholds until convergence. The trained GA-BP network can then be used to predict the shear strength under given combinations of density, sintering time, sintering temperature, and normal stress. The overall flowchart is shown in Fig. 18, and the main GA parameters are summarized in Table 2.

Figure 18 is very good.

Response: Thanks.

690

Figure 19: Do the serial numbers on these x- axes relate to Table 1 somehow? The way the trials/tests are numbered needs improvement and more consistency throughout the paper.

Response: Thank you for your comment. The numbers on the x-axis in Figure 19 represent the test results for a test set comprising 15% (67 groups) of all shear strength values (448 groups) selected at random; these numbers are unrelated to the item numbers in Table 1. We have added a clarification to the original text to avoid any ambiguity:

695 After training the neural network model, 15% of the total dataset (67 samples), which

700 were not part of the training set, were randomly selected as the test set. The accuracy  
of the trained neural network was then evaluated by comparing the predicted results  
with the actual values.

Figure 19(a): The agreement between the measured data and the modeled data from the  
705 neural network looks a little too good. The level of validation is sky high. I'm wondering  
if the model is overfit, considering 80% of the empirical dataset was used for calibration.  
Also, I'm not a neural network expert by any means, but isn't this a ton of computation  
for predicting only four variables?

**Response:** The question regarding neural networks has already been responded in  
710 [Comment R2.5 \(Overall\)](#).

L289: What is the "Connection Weights Method"? I don't see this mentioned anywhere  
else in the study.

**Response:** An explanation of the connection weight method has been added to the  
715 manuscript:

Fig. 18(b) illustrates the relative importance of each input variable to shear strength,  
calculated using the Connection Weights Method (Olden et al., 2004), which quantifies  
variable importance based on the raw connection weights between network layers.

720 **References:**

Olden, J.D.; Joy, M.K.; Death, R.G. An accurate comparison of methods for quantifying  
variable importance in artificial neural networks using simulated data. *Ecol.  
Model.*, 178, 389–397, <https://doi.org/10.1016/j.ecolmodel.2004.03.013>, 2004