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Shear and creep behaviour of frozen sand at different relative densities

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ABSTRACT: Artificial ground freezing (AGF) is an advanced, sustainable, and environmentally friendly construction technique that temporarily increases the subsoil's stiffness and strength and provides water tightness. It can be implemented effectively in urban conditions where the risk of using other subsoil improvement, water tightening, and dewatering techniques can be high due to complex or partially unknown boundary conditions and the consequences of damage. Indeed, the shear and creep strength of frozen granular soils depends on a number of aspects, including temperature, rate, stress state and volumetric composition. Considering the influence of the volumetric composition on the mechanical behaviour of frozen soils, it is important to note the challenges posed by the natural variability of soils in-situ. Here, changes in relative density within a soil layer of otherwise similar composition and state greatly complicate the characterization of frozen soil mechanical behaviour. For instance, under fully saturated soil conditions, the proportion of pore water available for freezing varies with the relative density, ultimately affecting the resultant ice content, which later contributes to the increased frozen soil shear and creep strength. In addition, with respect to the ultimate and service limit state design of frozen soil bodies, it is crucial to evaluate the differences in frozen soil shear and creep strength as a function of initial soil relative density. Therefore, this paper introduces shear and creep tests on frozen Karlsruhe sand with varying initial relative densities, as well as freezing tests from the literature on two different frozen sands. This comprehensive experimental database derives a linear relationship between shear and creep strength and the initial frozen soil relative density that is largely independent of rate and temperature.

KEYWORDS: Frozen soil, shear, creep, relative density.

1 INTRODUCTION

In general, frozen granular soil is a complex multiphase material consisting of four components: mineral grains, unfrozen pore water, frozen pore water, and air voids. Particularly in frozen saturated coarse-grained soils with low fine content, only two components are relevant as the grain skeleton is embedded in the ice matrix. The shear resistance of the frozen soil results from a complex interaction between the grain skeleton and the ice matrix. On the one hand, the ice hinders the dilatancy of the grain skeleton, leading to an increase in grain-to-grain contact forces and shear resistance. On the other hand, the grains retard the development and spreading of cracks in the ice matrix and enhance the shear resistance of the ice. Probably, the most interesting and distinctive feature of frozen soils is their rate- and temperature-dependence resulting from the viscous behaviour of the ice. Following, the essential uniaxial creep behaviour of frozen soils is briefly described and explained for single-stage loading conditions and thus under a constant uniaxial creep stress. At first, the axial strain rate decreases (primary creep) and then increases (tertiary creep) with time. The testing time at which the minimum axial strain rate (or, in general, minimum creep rate) $\dot{\varepsilon}_m$ (secondary creep) is reached and the tertiary creep begins is called lifetime t_m. After reaching the lifetime t_m, frozen granular soils under constant load fail inexorably beyond this time (Orth, 1986). In general, the described viscous behaviour of frozen soils depends on the granulometric properties of the soil, the density, the water -, ice-, and solid-content (volumetric composition of the frozen soil), the temperature, and the stress state.

As one of the first experimental studies, Goughnour and Andersland (1968) investigated the influence of increasing sand fraction in ice-sand mixture specimens for saturated conditions (constant degree of saturation) on the shear strength by uniaxial compression tests. They started with pure ice samples and then tested mixed ice-sand samples with increasing percentages of sand by volume V_{Sand} so that the total sand content in the samples increased under saturated conditions. Figure 1 includes some of these test results and their corresponding mechanical interpretation by Ting et al. (1983).

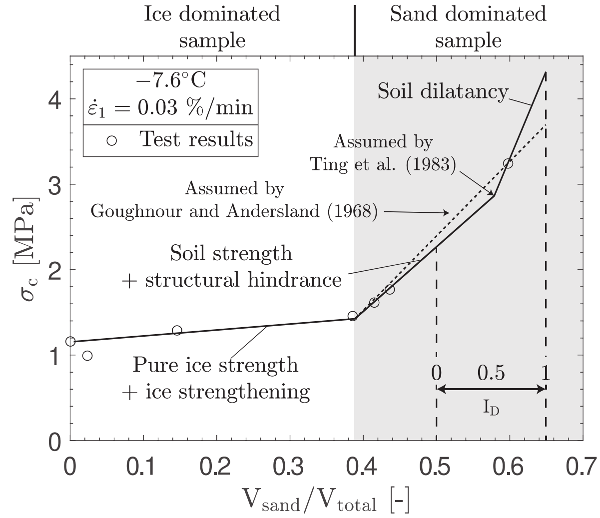

Figure 1. Increase of uniaxial compression strength σ_c with increasing sand volume V_{Sand} of frozen saturated Ottawa sand specimens. Test data (symbols) after Goughnour and Andersland (1968) and their interpretation (lines) after Ting et al. (1983). Figure reproduced after Ting et al. (1983) and partially modified.

Even with low volume percent of sand V_{Sand} in the sample, the uniaxial compression strength σ_c was higher than that for pure ice ($V_{Sand} = 0$), but increased relatively slowly, indeed, linearly with V_{Sand} and, thus, the relative density of the frozen soil I_D. Up on a certain point of about 40 % sand by volume, σ_c increased more steeply with V_{Sand}, indicating an influence change of V_{Sand} on the shear strength.

As can be seen in Figure 1, Goughnour and Andersland (1968) and Ting et al. (1983) assumed mostly linear relationships between σ_c and the relative density of the frozen soil I_D, although the available amount of experimental data for this range was very limited to support this assumption. Since then, many experimental studies, e.g. Andersen et al. (1995), have contributed to a better understanding of the relative density on the mechanical frozen soil behaviour. However, most of these studies have focused on the shear strength, conducting uniaxial and triaxial compression tests at different relative densities I_D. The important link and combination of shear and creep tests with the same material under varying I_D is often missing. Therefore, the influence of I_D on the rate-, stress-, and temperature-dependent shear and creep strength of frozen soils is not yet fully understood and will be investigated in this study.

2 METHODS

2.1 *Testing material*

This study includes three different, mostly uniform sands:

- Karlsruhe sand (KAS) is a coarse to medium quartz sand from the Rhine River (Karlsruhe, Germany); for details, see also Schindler (2024).
- Ottawa sand (OTS) is a medium sand obtained from Ottawa (Illinois, USA); for details, see Parameswaran (1980).
- Manchester fine sand (MFS) is a quartz and feldspar fine sand obtained from the banks of the Merrimack River (New Hampshire, USA); for details, see Andersen (1991).

In this study, frozen Karlsruhe sand (KAS) was experimentally investigated and tested, while freezing tests on frozen Ottawa sand (OTS) and frozen Manchester fine sand (MFS) were adapted from the literature. Figure 2 depicts the corresponding grain size distributions of all three materials.

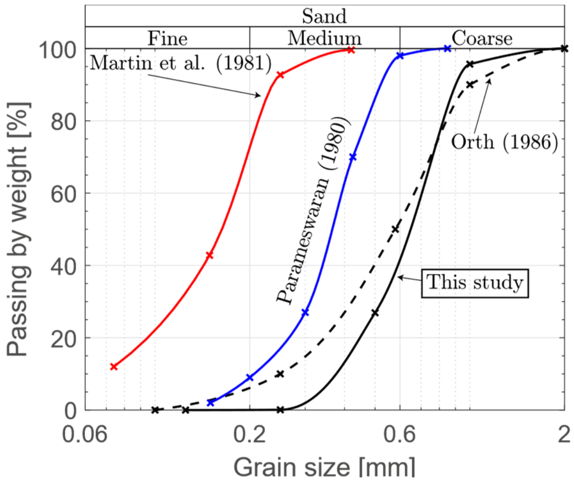

Figure 2. Grain size distributions of the investigated frozen sands. Black lines: Karlsruhe sand (KAS); Blue line: Ottawa sand (OTS); Red lines: Manchester fine sand (MFS).

2.2 *Sample preparation and testing program*

The tested Karlsruhe sand (KAS) samples were prepared in a polyamide box consisting of four moulds using the water-sedimentation method (WSM). Using WSM led to a mostly loose state of the samples. In order to obtain the target value of the specific frozen soil relative density for performing a certain test, the sample box was mounted on a vibrating table, and a specific time of vibration was applied at a constant predefined amplitude. Note that it is difficult to achieve a full saturation of the soil samples by using WSM alone. In this study, the specimens were not fully saturated and had an average saturation degree of 88 %.

A total of 58 uniaxial compression tests and 53 single-stage creep tests were conducted on frozen KAS at various rates, stresses, temperatures and relative densities. The essential testing results are summarised in the following sections.

3 EXPERIMENTAL RESULTS

3.1 *Uniaxial compression tests*

To establish a quantitative relationship between uniaxial compression strength σ_c and the relative density of the frozen soil I_D, Figure 3 compares σ_c at -10°C with the relative density I_D. It includes our own test data with frozen KAS and data with frozen KAS and Ottawa sand (OTS) from the literature.

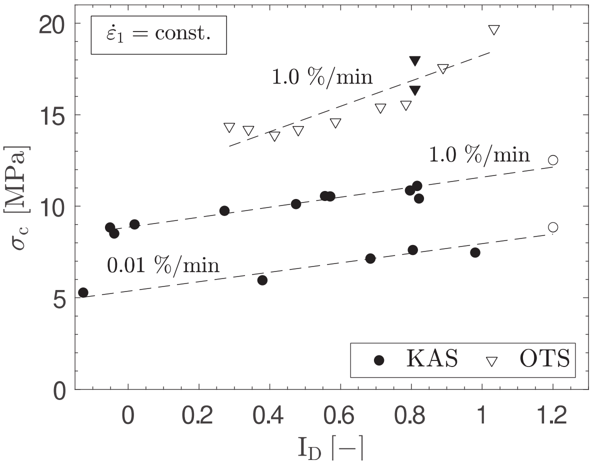

Figure 3. Comparison of uniaxial compression strength σ_c, and relative density I_D at -10°C.
KAS: our own tests (filled symbol) and after Orth (1986) (open symbols). OTS data after Baker and Konrad (1985) (open symbol) and Parameswaran (1980) (filled symbols).

As can be seen in Figure 3, our own KAS test results and additional data from Orth (1986) indicate a linear relationship between σ_c and I_D. In fact, this proportional behaviour holds for different axial strain rates based on the comparison of tests with $\dot{\varepsilon}_1 = 1.0$ %/min and $\dot{\varepsilon}_1 = 0.01$ %/min Test results of frozen OTS in Figure 3 from the literature essentially confirm our experimental findings, although the data scatter is stronger. We point out that the OTS data could also indicate a non-linear relationship between σ_c and I_D, which, however, is not provided by the KAS data.

To sum up, based on our own uniaxial compression tests and data from the literature, we found that shear strength increases linearly with relative density for coarse-grained frozen soil at high degrees of saturation. The observed approximate linearity supports and validates previous assumptions made from the literature, which were associated with uncertainties due to the limited amount of data and the scatter.

3.2 *Uniaxial creep tests*

After analysing the influence of relative density on the shear strength of frozen coarse-grained soils, this section deals with its influence on creep behaviour under uniaxial loading.

For this purpose, again, we use and evaluate both our own frozen KAS tests and data from the literature.

Figure 4 and Figure 5 summarise and highlight our experimental findings in terms of the dependence of the frozen soil creep strength on the relative density I_D.

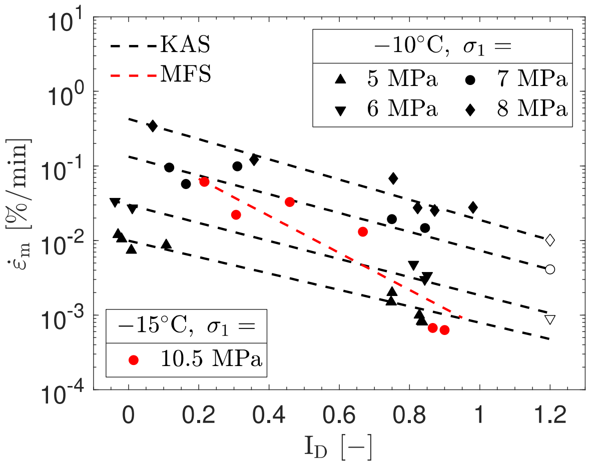

Figure 4. Minimum axial strain rate $\dot{\varepsilon}_m$ over relative density I_D in uniaxial creep tests. KAS: Our own tests (filled symbols) and after Orth (1986) (open symbols). MFS after Ting (1981).

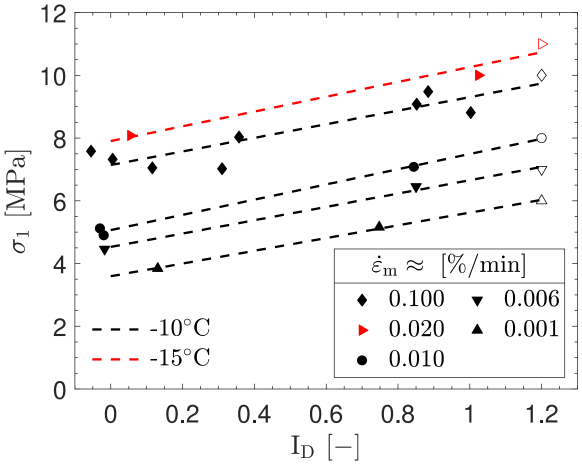

Figure 5. Uniaxial creep stress σ_1 over relative density I_D for different obtained minimum axial strain rates $\dot{\varepsilon}_m$. Note that $\dot{\varepsilon}_m$ is a testing result. KAS: Our own tests (filled symbols) and after Orth (1986) (open symbols).

Based on the results of Figure 4 and Figure 5, the following key insights can be derived.

First, for creep tests on KAS, a strong linear correlation is evident between I_D and the logarithm of $\dot{\varepsilon}_m$ for a wide range of different axial stresses (see Figure 4). For comparison purposes, experimental results with MFS from Ting (1981) are also depicted with red points in Figure 4. For MFS, the log-linear relationship appears to be a quantitatively poorer fit to the test data, although the qualitative trend is still satisfactorily captured. Deviations from a log-linear relationship in the MFS tests could be due to more pronounced scatter, measurement inaccuracies, and the overall limited number of seven tests under a single axial load and temperature compared to the sophisticated and more comprehensive KAS database.

In Figure 5, the axial creep stress σ_1, required to achieve a certain minimum axial strain rate $\dot{\varepsilon}_m$, is plotted against I_D. The presented data includes uniaxial creep tests at -10°C (black symbols) and -15°C (red symbols). Note that it is not possible to intentionally generate a specific $\dot{\varepsilon}_m$ in load-controlled tests since only σ_1 can be controlled during uniaxial creep tests. Thus, $\dot{\varepsilon}_m$ is a test result induced by σ_1 rather than an input parameter for a creep test. Based on the creep test results in Figure 5, a linear relationship between σ_1 and I_D can be established when comparing similar values of $\dot{\varepsilon}_m$. In fact this relationship appears to be independent of the temperature, as the slope of the black and red lines is visibly almost identical. Moreover, as I_D increases, a higher value of σ_1 is required to attain the same $\dot{\varepsilon}_m$, additionally confirming the previous results highlighted in Figure 4.

3.3 *Triaxial testing*

So far, the analysis has predominantly focused on uniaxial stress conditions. In this section, we expand the scope to include three-dimensional aspects by examining the influence of relative density I_D for different triaxial stress states and, thus, confinements. Instead of conducting our own triaxial freezing tests on frozen KAS, we use comprehensive testing data from the literature on frozen Manchester Fine Sand (MFS) for this purpose. Andersen (1991) reported triaxial compression tests on frozen MFS with a wide range of different temperatures, strain rates, confinements, and relative densities. In order to derive a fundamental relationship between the relative density I_D, the confining pressure σ_3, and the peak strength q_u, Figure 6 plots q_u against I_D using triaxial test data on frozen MFS.

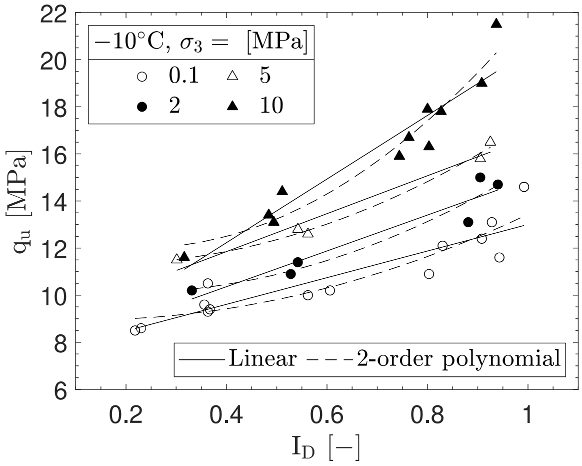

Figure 6. Comparison of the peak deviator q_u with the relative density I_D and their regressions (lines) for different confinements σ_3 in triaxial compression tests with $\dot{\varepsilon}_1 = 0.18$ %/min. Data after Andersen (1991).

In Figure 6, the shear strength q_u increases with the relative density I_D under constant confinement, consistent over a wide range of different confining pressures σ_3 from 0.1 MPa to 10 MPa and temperatures. It is noteworthy that confined compression tests at $\sigma_3 = 0.1$ MPa closely resemble unconfined compression tests due to the low level of confinement, aligning with the previously established linear relationship for uniaxial stress conditions in Section 3.1. In general, in Figure 6, both regression approaches (solid and dashed lines) show good agreement with the experimental data, even though the polynomial fit at relatively high confinements of $\sigma_3 = 10$ MPa has higher accuracy than the linear approach.

Summarising, the influence of the relative density I_D under different confinements on the shear strength of frozen soils is essentially comparable to that under uniaxial stress conditions, as the peak deviator stress q_u increases approximately linearly with increasing I_D under low and high confining pressures.

4 CONCLUSIONS

The relative density I_D of frozen granular soils affects the compression strength σ_c and the creep strength σ_1 under uniaxial loading conditions. First, it was found that the shear strength increases linearly with increasing relative density. In terms of the uniaxial creep behaviour, when comparing a constant minimum strain rate $\dot{\varepsilon}_m$, the axial creep stress σ_1 required to achieve a specific value of $\dot{\varepsilon}_m$ increases linearly with $\mathrm{I_D}$. These essential relationships have been experimentally confirmed for a wide range of different stress states, temperatures, and relative densities at a constant degree of saturation.

In conclusion, σ_c and σ_1 increase linearly, mostly rate- and temperature-independently, with $\mathrm{I_D}$. It is possible to describe the evolution of the compression strength σ_c and the creep strength σ_1 for different strain rates and temperatures within a single relationship and to combine this relationship with a unique one for its dependence on the relative density $\mathrm{I_D}$. While triaxial stress states are beyond the primary scope of our experimental work, we summarized extensive triaxial compression test data from the literature to identify the effect of $\mathrm{I_D}$ on the mechanical frozen soil behaviour under confinement. Apart from the general increase in shear strength with increasing confining pressure for loose to dense states, the fundamental relationships between relative density $\mathrm{I_D}$ and shear strength established from uniaxial conditions also approximate well for triaxial conditions.

5 ACKNOWLEDGEMENTS

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