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# Experimental observations on the creep behaviour of frozen soil

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# Abstract

Constitutive models in the literature for creep of frozen soil are based on the direct use of <sup>5</sup> time counted from the onset of creep. An explicit time dependence in a constitutive equation <sup>6</sup> violates the principles of rational mechanics. No change in stress or temperature is allowed <sup>7</sup> for during creep, using the time-based formulations. Moreover, the existing descriptions need <sup>8</sup> much verification and improvement on the experimental side as well. <sup>9</sup>

Creep behaviour of artificially frozen sand was evaluated experimentally. Novel testing methods <sup>10</sup> were used and new insights into the creep behaviour of frozen soil were gained. <sup>11</sup>

Creep rate under uniaxial compression was examined with different kinds of interruptions, like 12 unloadings or overloadings. Experimental creep curves were presented as functions of creep 13 strain. They were brought to a dimensionless form which describes the creep universally, 14 despite changes in stress or temperature. Possible anisotropy of frozen soil was revealed in the 15 creep tests on cubic samples with changes of the loading direction. Using the particle image 16 velocimetry (PIV) technique, information on the lateral deformation and the uniformity of 17 creep were obtained. Volumetric creep of unsaturated frozen soil under isotropic compression 18 was demonstrated to be due to the presence of air bubbles only. 19

*Keywords:* creep, rate dependence, artificially frozen sand, uniaxial compression, anisotropy, <sup>20</sup> PIV, dilatancy, isotropic compression <sup>21</sup>

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## 1. Introduction

Artificial ground freezing is a technique used as a temporary soil stabilisation and insulation 23 method, e.g., during tunnel constructions in urban areas. It often turns out to be the most 24 efficient and environmental friendly solution to provide a temporary earth support [18]. In most 25 cases, the creep of frozen soil, rather than its short-term strength, is of the primary importance. 26 Present evaluation of the creep deformation of frozen soil is oversimplified. High safety factors 27 or basing on the engineering experience are commonly applied. This can result in expensive 28 design or in geotechnical failures. A recent example of such failure is the collapse of a tunnel 29 in Rastatt, Germany [8]. It indicates that the mechanical behaviour of frozen soil is not well 30 understood as yet. 31

The most popular currently used mathematical description of creep in frozen soil [2, 3, 17] is non-autonomous as it is explicitly dependent on the time elapsed from the onset of creep. The sefficiency and safety of the ground freezing technology could be increased by incorporation of set a sound theoretical model. A new state variable that dictates the rate of creep and ensures the set autonomy of constitutive description should be developed. Novel aspects, like the volumetric such model.

In geomechanics, there is no generally accepted set of state variables that governs the rate of creep in frozen soil except for the stress,  $\boldsymbol{\sigma}$ , the temperature,  $\Theta$ , and the void ratio, e. In clayey soil at positive temperatures, such variable is the overconsolidation ratio, OCR. It is not easy, however, to adopt the creep rate  $\dot{\boldsymbol{\varepsilon}}^{vp}(OCR)$  known from [24] for frozen soil because the concept of the effective stress in frozen soil has not been established as yet. Besides, the OCR-based models are not capable to describe the tertiary creep.

To develop a novel constitutive framework, the creep of frozen sand was inspected in the frost laboratory at the Institute of Soil Mechanics and Rock Mechanics (IBF) at the Karlsruhe Institute of Technology (KIT). Based on the new experimental observations, the shortcoming of direct time dependence is evident. Simulation of creep with interruptions, like unloadings or overloadings, using an explicit time function is impossible.

Present state of the art on the creep behaviour of frozen soil is given as first. Novel experiments <sup>50</sup> required for the formulation of an improved creep description are then described and their results <sup>51</sup>

# Notation

Bold-face letters, like  $\boldsymbol{\sigma}$ , are second rank tensors. The geotechnical sign convention with compression positive is applied to stress  $\boldsymbol{\sigma}$  and strain  $\boldsymbol{\varepsilon}$ . The elastic part of strain is denoted as  $\boldsymbol{\varepsilon}^{\text{el}}$  55 and the visco-plastic one as  $\boldsymbol{\varepsilon}^{\text{vp}}$ . Uniaxial stress is understood as diagonal form  $\boldsymbol{\sigma} = \text{diag}(\sigma, 0, 0)$ . 56 The basic variables are given below. 57

e	void ratio
E, K	elastic constants
p	isotropic pressure
S	degree of saturation
t	time
$t_m$	standing time
$\mathbf{u}(\mathbf{X},t)$	displacement field in material description
V	volume
X	reference location

strain tensor (compression positive)
deformation field in material description
visco-plastic strain measured in creep tests under uniaxial stress
creep strain at $\dot{\varepsilon}_m$
minimum creep rate
volumetric strain $\varepsilon_{\rm vol} = {\rm tr}\boldsymbol{\varepsilon}$
maximum volumetric creep strain
volumetric content of $\sqcup,\mu^{\sqcup}=V^{\sqcup}/V$
total stress tensor (compression positive)
component of uniaxial stress $\boldsymbol{\sigma} = \text{diag}(\sigma, 0, 0)$
effective stress in soil skeleton
temperature [°C]

Ц.	material rate of $\sqcup$ , $\dot{\sqcup} = \partial \sqcup / \partial t = \sqcup_{,t}$
$\sqcup_{\mathrm{hor}}, \sqcup_{\mathrm{vert}}$	horizontal and vertical component
$\mathrm{tr}\sqcup$	trace of $\sqcup$ , e.g., tr $\boldsymbol{\sigma} = \sigma_{ii}$

The essential abbreviations are listed below.

А	cubic (suited for testing of <u>a</u> nisotropy) frozen sample tested without the PIV
AF	cubic (suited for testing of <u>a</u> nisotropy) frozen sample tested with the PIV
	(i.e., ger $\underline{f}otografiert$ )
С	standard (uninterrupted) creep test
CurC	<u>creep</u> test with an <u>unloading-r</u> eloading cycle followed by <u>creep</u>
CoC	<u>creep</u> test with an <u>overloading</u> followed by <u>creep</u>
$\mathrm{CoCrC}$	<u>c</u> reep test with an <u>o</u> verloading followed by <u>c</u> reep, <u>r</u> eloading and <u>c</u> reep
CA	<u>creep</u> test with a change of the loading direction (for examination of <u>a</u> nisotropy)
CI	$\underline{\mathbf{c}}$ reep test under $\underline{\mathbf{i}}$ sotropic compression
CSR	$\underline{c}$ onstant $\underline{s}$ train $\underline{r}$ ate
KFS	$\underline{\mathbf{K}}$ arlsruhe $\underline{\mathbf{F}}$ ine $\underline{\mathbf{S}}$ and
KS	cylindrical sample in a creep test (ger <u><math>K</math></u> riechtest) on frozen <u>s</u> and
PIV	<u>particle image velocimetry</u>

## 2. Creep of frozen soil

Three stages of creep are defined for frozen soil, Fig. 1a, judging by the deformation rate as <sup>60</sup> a function of time: <sup>61</sup>

- primary (decreasing)
- secondary (constant)
- *tertiary* (increasing),

see Fig. 1b. One interpretes the secondary stage as an inflection point of the  $\varepsilon^{vp} - t$  plot (with the corresponding minimum of the  $\dot{\varepsilon}^{vp} - t$  plot) [17, 19, 25]. The creep rate  $\dot{\varepsilon}^{vp}$  in frozen soil is commonly presented as function of time t and not of strain  $\varepsilon^{vp}$  as in the case of pure ice [22].

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Figure 1: Frozen soil: a) schematic microstructure and b) creep under uniaxial stress  $\boldsymbol{\sigma} = \text{diag}(\sigma, 0, 0) = \text{const}$ applied at t = 0 with indicated creep stages: strain  $\varepsilon^{\text{vp}}$  as function of time t and strain rate  $\dot{\varepsilon}^{\text{vp}}$  as function of time t.

# 2.1. Creep strain $\varepsilon_m$ at the slowest creep rate $\dot{\varepsilon}_m$

If a standard (uninterrupted) creep test is conducted under stress  $\sigma = \text{const}$  and temperature  $\Theta = \text{const}$ , the minimum creep rate  $\dot{\varepsilon}_m$  is achieved at  $t_m$ , see Fig. 1b, after which the creep representation accelerates. The strain accumulated until  $t_m$ ,  $\eta$ 

$$\varepsilon_m = \int_0^{t_m} \dot{\varepsilon}^{\rm vp} \, \mathrm{d}t = \mathrm{const}\,,\tag{1}$$

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turns out to be a material constant [17, 26], i.e., it is independent of  $\sigma$  and  $\Theta$ . This independence values also observed in the tests reported in Sec. 4.

#### 2.2. Minimum creep rate as a material function $\dot{\varepsilon}_m(\sigma,\Theta)$

Let us now consider two series of standard creep tests, Fig. 2. Tests in the first series differ by the values  $\sigma^{(i)}$  of stress and in the second one by the values  $\Theta^{(i)}$  [°C] of temperature with i = 1, 2, 3. It is evident that the minimum creep rate  $\dot{\varepsilon}_m$  increases with  $\sigma$ , see Fig. 2a–b, and with  $\Theta$ , Fig. 2c–d. Hence, the minimum creep rate  $\dot{\varepsilon}_m$  is a function of both,  $\sigma$  and  $\Theta$ . A possible form of function  $\dot{\varepsilon}_m(\sigma, \Theta)$  was defined in [2, 3, 17] and another one in [23].

#### 2.3. Normalised creep curves

Creep curves  $\varepsilon^{\rm vp}(t)$  and  $\dot{\varepsilon}^{\rm vp}(t)$  obtained from experiments, Fig. 2, during a standard (uninterrupted) creep test can be "normalised" as follows: values corresponding to the minimum creep rate:  $\varepsilon_m$ ,  $\dot{\varepsilon}_m$  and  $t_m$  are used in  $\varepsilon^{\rm vp}/\varepsilon_m(t/t_m)$  and  $\dot{\varepsilon}^{\rm vp}/\dot{\varepsilon}_m(t/t_m)$  as shown in Fig. 3. After such normalisation all experimental curves coincide to a unique curve.



Figure 2: Creep curves in two series of standard creep tests: a)  $\varepsilon^{\rm vp}(t)$  and b)  $\dot{\varepsilon}^{\rm vp}(t)$  in the first series (tests differ by stress  $\sigma$ ); c)  $\varepsilon^{\rm vp}(t)$  and d)  $\dot{\varepsilon}^{\rm vp}(t)$  in the second series (tests differ by temperature  $\Theta$ ).



Figure 3: Normalised functions: a)  $\varepsilon^{\rm vp}/\varepsilon_m(t/t_m)$  and b)  $\dot{\varepsilon}^{\rm vp}/\dot{\varepsilon}_m(t/t_m)$ .

## 2.4. Purely volumetric creep

Contrarily to the case of the deviatoric creep, experimental data on the purely volumetric creep of frozen soil can be hardly found in the literature. Several creep tests on frozen sand under isotropic pressure are reported in [4]. Volumetric deformation was measured via the volume change of the cell fluid. The air bubbles in this fluid were not addressed in [4] and hence the results are not reliable. According to the experience made in this study, air bubbles in the cell fluid can strongly influence the measured volumetric strain of the tested samples.

## 3. Introduction to experiments

Much data on the creep behaviour of frozen sand were provided by Eckardt [5, 6, 7], Orth [17] 93 and Ting [25] in the 80's. Most of these experiments were carried out under uniaxial stress 94 either as constant strain rate (CSR) or as creep tests. A few tests under uniaxial tension [7] and 95 under triaxial stress [17] are also reported. The results from [17] were summarised in the form of 96 several empirical equations describing the creep behaviour of frozen soil depending on the stress 97 level  $\sigma$  and on the temperature  $\Theta$ . This was a starting point for the constitutive description 98 of the rate-dependent behaviour in frozen soil [2, 3]. Some creep tests with overloadings were 99 conducted in [5]. However, most observations in [17, 25] are applicable to a nearly constant 100 load only. Simulation of creep with interruptions (unloadings, overloadings, reloadings) using 101 the time-based formulations is not possible. 102

The description of creep proposed in [17] is based on the standing time  $t_m$  at  $\sigma = \text{const}$  until 103 the minimum creep rate  $\dot{\varepsilon}_m$  is reached. Both,  $t_m$  and  $\dot{\varepsilon}_m$ , are measurable. Additional aspects 104 of creep behaviour were investigated under uniaxial stress in this research. These aspects are 105 listed below and described further in Sec. 4. 106

- Interruptions and recovery of the creep rate 107 In order to demonstrate the main shortcoming of the standing time concept, temporary 108 (1 h to 7 days) unloadings of samples were conducted. A variety of further interruptions, 109 i.e., different sets of overloadings and reloadings, allowed an accurate inspection of the 110 creep curves.
- Temperature dependence It was essential to investigate how the temperature affects the creep curve.
  - Dilatancy and distribution of deformation

Particle image velocimetry (PIV) technique allowed the measurement of volumetric de-115 formation  $\varepsilon_{\rm vol}^{\rm vp}$  during creep under uniaxial stress and enabled a better insight into the 116 distribution of deformation within the frozen sample. 117

• Anisotropy effects

Anisotropy effects may be very strong in the case of pure ice due to the recrystallization 119 [22]. No experimental evidence could be found in the case of frozen soil. Hence the 120

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possible effects of anisotropy were investigated on frozen sand. Before  $t_m$ , cubic samples 121 were shortly unloaded, rotated by  $90^{\circ}$  and then reloaded to study whether such operation 122 can affect the creep rate  $\dot{\varepsilon}^{\rm vp}$ . 123

Additionally, some volumetric creep tests under isotropic compression were conducted in the 124 course of a bachelor thesis at IBF, KIT [35] and their results are summarised in Sec. 5. 125

• Purely volumetric creep

Volumetric creep of pure ice under constant isotropic stress is related to the presence of 127 air bubbles in ice [12]. Unfortunately, there is a lack of lab data for frozen soil. Creep 128 tests under isotropic stress are technically troublesome but they confirmed the volumetric 129 creep of frozen soil to be due to the presence of air bubbles only. 130

Apart from the creep behaviour of artificially frozen sand, other important engineering prob-131 lems related to frozen soils, like the frost heave in fine-grained soils, have been studied in the 132 literature. The corresponding experimental evidence and constitutive models are reported, for 133 example, in [14, 31, 34]. 134

# 4. Creep tests under uniaxial compression

Creep tests under uniaxial stress are essential for the formulation of a novel constitutive de-136 scription. All experiments were conducted in the cold room of the frost laboratory at IBF 137 within a doctoral study and a comprehensive lab report is given in [23]. Stress and tempera-138 ture levels were chosen in the tests to cover practical values from applications of the ground 139 freezing technology, particularly in tunnel engineering. 140

# 4.1. Tested material, sample preparation and experimental procedures

All tests were conducted on Karlsruhe Fine Sand (KFS) which is well-known from numerous 142 works elaborated at IBF, KIT [9, 13, 29, 33]. Basic properties of the tested material are given 143 in Tab. 1. 144

Two kinds of frozen samples were prepared: conventional cylindrical ones (KS) and cubic ones 145 tested either without (A) or with the PIV (AF). Cylindrical samples had the diameter of 10 cm 146 and the height of 15.5 cm. Samples for testing of anisotropy were chosen to have the cubic 147

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Table 1: Basic properties of Karlsruhe Fine Sand (KFS).  $C_u$  $d_{50}$  $\rho_s$  $e_{\rm max}$  $e_{\min}$  $\varphi$ 0  $g/cm^3$ mm ---1.52.651.0540.67733.10.14

form. Such form also facilitated the processing of data in the case of tests with the PIV. Size 148 of the cubes was constrained by the available freezing equipment to  $7 \times 7 \times 7$  cm<sup>3</sup>. 149 Sample preparation was aimed at the reproducibility, full saturation and homogeneity of porosity. Void ratio *e*, degree of saturation *S* and density index  $I_D$  of all samples referred in this 151 paper are given in Tab. 2. 152

Table 2: Void ratio e, density index  $I_D$ and degree of saturation S: cylindrical samples (KS), cubic samples (A) and cubic samples tested with the PIV (AF).

Sample	S	e	$I_D$
1201	-	-	-
KSI	0.95	0.88	0.47
KS2	0.99	0.84	0.58
KS3	1.00	0.85	0.55
KS4	0.97	0.87	0.48
KS7	0.97	0.72	0.89
KS8	0.98	0.70	0.94
KS9	0.98	0.71	0.91
KS10	0.99	0.73	0.87
KS11	0.98	0.71	0.91
$A1^{a}$	-	0.73	0.87
$A2^{a}$	-	0.72	0.89
A3	0.97	0.72	0.89
A5	0.96	0.73	0.85
A6	0.96	0.72	0.90
A7	0.96	0.72	0.88
A8	0.95	0.72	0.89
AF1	0.93	0.77	0.76
AF2	0.95	0.76	0.79
AF5	0.96	0.74	0.83
AF6	0.96	0.76	0.79
AF7	0.96	0.76	0.79
AF8	0.96	0.74	0.84
AF9	0.96	0.76	0.78
AF10	0.96	0.76	0.78
AF11	0.95	0.76	0.78
AF12	0.95	0.79	0.71
AF13	0.95	0.73	0.85
AF14	0.96	0.75	0.81
AF15	0.92	0.76	0.79
AF16	0.96	0.73	0.85
AF17	0.97	0.75	0.82
111. T I	0.31	0.10	0.04

<sup>a</sup> Dry mass of the sample was not measured after the test.

Data acquisition was done by the data logger of the hydraulic press. For the postprocessing, <sup>154</sup> a self-developed MATHEMATICA [30] package Freeze' was used. The scatter in results (creep <sup>155</sup> strain and its rate) was smoothed using a Gaussian kernel and the results were plotted in the <sup>156</sup> form of creep curves. Gaussian kernel with the radius r was applied and the smoothing caused <sup>157</sup> the loss of r first and r last measurements in each list of results. This can be seen in the <sup>158</sup> reported diagrams, e.g., the plotted  $\dot{\varepsilon}^{\rm vp}(\varepsilon^{\rm vp})$  curves do not start at  $\varepsilon^{\rm vp} = 0$ . <sup>159</sup>

Greased rubber pads were placed at the interfaces between the sample and the end plates of <sup>160</sup> the testing device to reduce friction and to improve the uniformity of stress distribution within <sup>161</sup> the sample. However, the strain measured via the displacement of the end plate during the test <sup>162</sup> includes a portion from the rubber pads with grease. The part of deformation resulting from <sup>163</sup> compression of these pads is called the *bedding error*. It was measured and taken into account <sup>164</sup> in the processing of data [23]. <sup>165</sup>

#### 4.3. Interruptions and recovery of the creep rate

From the practical point of view, a constitutive description should consider a general case of <sup>167</sup> creep interrupted by different sets of unloadings, overloadings, reloadings. For this purpose, <sup>168</sup> the existence of a unique creep curve  $\dot{\varepsilon}^{\rm vp}/\dot{\varepsilon}_m(\varepsilon^{\rm vp}/\varepsilon_m)$  specific to a given type of frozen soil is <sup>169</sup> postulated. This *universal creep curve* was verified by conduction of the tests with different <sup>170</sup> interruptions.

## 4.3.1. Standard (uninterrupted) creep tests (C)

To examine whether the interruptions affect the creep rate, the referential standard creep test 173 (C) will be used for comparison. 14 such C tests were carried out under various conditions. 174 Details on these tests are included in Tab. 3.

Note that the representation  $\dot{\varepsilon}^{\rm vp}(\varepsilon^{\rm vp})$  is common in the glaciological literature, e.g., [22]. The 176 advantage of  $\dot{\varepsilon}^{\rm vp}(\varepsilon^{\rm vp})$  over  $\dot{\varepsilon}^{\rm vp}(t)$  is due to the autonomy of  $\dot{\varepsilon}^{\rm vp}(\varepsilon^{\rm vp})$ . Hence, the creep rates 177 from all C tests are shown in Fig. 4 in the form of  $\dot{\varepsilon}^{\rm vp}(\varepsilon^{\rm vp})$  graphs. 178

Unfortunately, a considerable scatter of the test results can be seen in Fig. 4. No systematic  $_{179}$  relation of this scatter to discrepancies in the physical parameters of the samples, like the void  $_{180}$  ratio e, could be recognised. This scatter can be a consequence of the used lab technique.  $_{181}$  The novel preparation technique might have caused the heterogeneity of samples. Influence of  $_{182}$ 

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Figure 4:  $\dot{\varepsilon}^{\rm vp}(\varepsilon^{\rm vp})$  curves in all C tests at various  $\sigma$  and  $\Theta$  with indicated minima  $(\varepsilon_m, \dot{\varepsilon}_m)$ .

different lab techniques (like air-pluviation, water-pluviation) on the scatter in results should <sup>183</sup> be conducted. The problem of the scatter in results of experiments on frozen soils is addressed, <sup>184</sup> e.g., in [15]. <sup>185</sup>

Sample/	Type	Θ	$\sigma$	$t_m$	$\varepsilon_m$	$\dot{arepsilon}_m$
Test	of test	$^{\circ}\mathrm{C}$	MPa	$\min$	%	$\%/{ m min}$
KS2	С	-10	5	431.0	7.5	$1.1\cdot 10^{-2}$
KS9	С	-10	7	136.1	5.8	$2.7\cdot 10^{-2}$
KS10	С	-10	5	544.5	5.7	$5.0\cdot 10^{-3}$
KS11	С	-10	7	142.4	5.7	$2.6\cdot 10^{-2}$
$A2^{a}$	С	-10	5	-	-	-
$A6^{b}$	С	-10	5	1241.6	6.7	$2.8\cdot 10^{-3}$
AF1	С	-10	5	545.3	6.9	$7.3\cdot 10^{-3}$
AF2	С	-10	5	452.1	6.5	$8.0\cdot 10^{-3}$
AF8	С	-10	7	127.9	6.5	$3.3\cdot 10^{-2}$
AF9	С	-10	7	124.4	6.9	$3.7\cdot 10^{-2}$
AF12	С	-20	7	1375.6	7.4	$3.0\cdot 10^{-3}$
AF13	С	-15	7	156.2	6.7	$2.7\cdot 10^{-2}$
AF14	С	-15	7	376.2	7.6	$1.2\cdot 10^{-2}$
AF17	С	-5	4	57.4	6.6	$9.0\cdot10^{-2}$

Table 3: Summary of C tests.

<sup>a</sup> Sample was pressed out of the testing device during the primary creep due to a geometrical irregularity in the testing device.

<sup>b</sup> Sample demonstrated an anomalous behaviour.

The main shortcoming of  $\dot{\varepsilon}^{vp}(t)$  concept can be easily demonstrated by the creep test interrupted by a temporary unloading followed by reloading. The sample regains its previous rate of creep and this contradicts the direct dependence  $\dot{\varepsilon}^{vp}(t)$ .

4 tests with an unloading-reloading cycle (CurC) were carried out at  $\sigma = 5$  MPa and  $\Theta = 190$ -10 °C, see Tab. 4. During the primary creep, the samples were temporarily unloaded at 191  $t = 20\%...30\% \bar{t}_m$ . Mean value of the standing time  $\bar{t}_m$  is known from the referential C tests 192 from Tab. 3. Samples were quickly unloaded from  $\sigma = 5$  MPa to  $\sigma = 0.1..0.2$  MPa (= the 193 weight of piston in the testing device). 194

The durations of pauses were: 1 h, 24 h, 24 h and 7 days in the case of samples: AF6, AF10, 195 AF11 and AF15, respectively. After the interruption period (pause), the samples were reloaded 196 back to  $\sigma = 5$  MPa and the creep rate prior to the unloading was regained. Creep curves  $\varepsilon^{\rm vp}(t)$ 197 can be recovered after a time shift-back corresponding to the duration of the interruption, see 198 Fig. 5a–b. Creep rates  $\dot{\varepsilon}^{\rm vp}(\varepsilon^{\rm vp})$  were obtained using the shifted curves  $\varepsilon^{\rm vp}(t)$  from all CurC tests 199 and are plotted in Fig. 6. Recovery of the creep rate after the unloading period is evident. 200 No influence of the interruptions on the minimum creep rate  $\dot{\varepsilon}_m$  can be inferred from comparison 201 with 4 corresponding C tests from Fig. 4. Creep curves  $\dot{\varepsilon}^{\rm vp}(\varepsilon^{\rm vp})$  from all CurC tests are shown 202 together with the ones from the 4 referential C tests in Fig. 7. It follows from Fig. 7 that 203 the results from CurC tests lie within the experimental scatter obtained from the C tests. No 204 systematic influence of the duration of the unloading can be concluded. 205

Table 4: Summary of CurC tests and referential C tests (excluding failed test A2 and anomalous test A6).

Sample/	Trung of tost	Θ	σ	$\varepsilon_m$	$\dot{\varepsilon}_m$
Test	Type of test	$^{\circ}\mathrm{C}$	MPa	%	$\%/{ m min}$
KS2	C (ref.)	-10	5	7.5	$1.1\cdot 10^{-2}$
KS10	C (ref.)	-10	5	5.7	$5.0\cdot 10^{-3}$
AF1	C (ref.)	-10	5	6.9	$7.3\cdot 10^{-3}$
AF2	C (ref.)	-10	5	6.5	$8.0\cdot 10^{-3}$
AF6	CurC(1 h)	-10	5	7.3	$6.2\cdot 10^{-3}$
AF10	CurC(24 h)	-10	5	7.2	$9.5\cdot 10^{-3}$
AF11	CurC(24 h)	-10	5	7.5	$1.1\cdot 10^{-2}$
AF15	CurC(7 days)	-10	5	7.4	$1.5\cdot 10^{-2}$



Figure 5:  $\varepsilon^{vp}(t)$  curves in CurC tests with indicated inflections  $("t_m", \varepsilon_m)$  (Standing time has no meaning and hence is denoted as "t\_m".): a) unloading periods are included; b) curves are shifted back in time by duration of unloading.



Figure 6:  $\dot{\varepsilon}^{vp}(\varepsilon^{vp})$  curves in CurC tests with indicated minima  $(\varepsilon_m, \dot{\varepsilon}_m)$ . An additional interruption can be seen in test AF15 after reloading. It is due to a failure in the control system.



Figure 7:  $\dot{\varepsilon}^{\rm vp}(\varepsilon^{\rm vp})$  curves in CurC tests and referential C tests with indicated minima  $(\varepsilon_m, \dot{\varepsilon}_m)$ .

Creep curve was also tested with other interruptions. Two types of creep tests with overloadings/reloadings were carried out on 6 samples at  $\Theta = -10$  °C, see Tab. 5. Before the slowest creep rate was achieved, samples from the first group (CoC) were only overloaded. They reached  $\dot{\varepsilon}_m$  under such increased stress. Samples in CoCrC tests were at first overloaded and then reloaded back to the previous stress. Hence, the minimum creep rate was obtained under the initial load.

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Similarly to the CurC tests, creep of all (but KS1) samples was interrupted at  $t = 20\%...30\% \bar{t}_m$ .<sup>213</sup> Mean value of the standing time  $\bar{t}_m$  could be determined basing on the referential C tests, see<sup>214</sup> Tab. 3. Samples from the second group (CoCrC) were unloaded to the initial stress after<sup>215</sup> 20..30 min of the overloading.<sup>216</sup>

KS1 was the first tested sample. It was meant to be a C test under  $\sigma = 3.5$  MPa but the minimum rate was not achieved at the expected time. Hence the sample was gradually overloaded. <sup>218</sup> For this reason KS1 is counted among the CoC tests. <sup>219</sup>

Creep curves  $\varepsilon^{vp}(t)$  from all CoC and CoCrC tests are given in Fig. 8. Interpretation of the <sup>220</sup> results is now somewhat more complicated than previously, in CurC tests. In the case of CoC <sup>221</sup> tests, the initial  $\sigma = 5$  MPa leaves a considerable creep deformation. In CoCrC tests, also <sup>222</sup> a significant creep strain is accumulated under the overload. <sup>223</sup>

The regained (after reloading) part of  $\varepsilon^{vp}(t)$  from a CoCrC test could be possibly shifted forward 224 in time until it meets the referential curve at the same creep strain. However, this only confirms 225 the invalidity of time as an argument in the creep rate function. A general description of the 226 creep behaviour basing on the time representation in the case of overloading is impossible. 227 Summing up, no clear conclusions can be drawn about the influence of overloadings/reloadings 228 on the creep curve judging by  $\varepsilon^{\rm vp}(t)$ . However, curves  $\dot{\varepsilon}^{\rm vp}(\varepsilon^{\rm vp})$  can be at least directly com-229 pared. Time-dependent description  $\dot{\varepsilon}^{\rm vp}(t)$  cannot be generalised. Creep rates from the CoC 230 and CoCrC tests are given in Fig. 9 seperately depending on stress  $\sigma$  at which the tertiary creep 231 was approached. These curves are additionally plotted together with the referential C tests in 232 Fig. 10. 233

It can be seen in Fig. 9a that the behaviour of sample KS7 stands a bit aside from the others <sup>234</sup> because KS7 achieved quite slower  $\dot{\varepsilon}_m$ . However, this deviation seems to be within the experimental scatter as shown in Fig. 10a. Apart from that, the target creep curve  $\dot{\varepsilon}^{vp}(\varepsilon^{vp})$  is <sup>236</sup> always regained, see Fig. 10a–b. Neither the minimum rate  $\dot{\varepsilon}_m$  is pronouncably affected by the <sup>237</sup> overloadings/reloadings.

Additionally, the creep rate  $\dot{\varepsilon}^{\rm vp}(\varepsilon^{\rm vp})$  is plotted for CoCrC tests and the referential C tests at <sup>239</sup> both,  $\sigma = 5$  MPa and  $\sigma = 7$  MPa, Fig. 11. It can be observed how  $\dot{\varepsilon}^{\rm vp}$  switches between the <sup>240</sup> creep isobars depending on the current stress level. <sup>241</sup>



Figure 8:  $\varepsilon^{vp}(t)$  curves in CoC and CoCrC tests with indicated inflections (" $t_m$ ",  $\varepsilon_m$ ). (Standing time has no meaning and hence is denoted as " $t_m$ ".)



Figure 9: CoC and CoCrC tests with indicated minima  $(\varepsilon_m, \dot{\varepsilon}_m)$ : a)  $\dot{\varepsilon}^{vp}(\varepsilon^{vp})$  curves in CoC and CoCrC tests in which  $\dot{\varepsilon}_m$  was achieved at  $\sigma = 5$  MPa; b)  $\dot{\varepsilon}^{vp}(\varepsilon^{vp})$  curves in CoC tests in which  $\dot{\varepsilon}_m$  was achieved at  $\sigma = 7$  MPa.



Figure 10: CoC and CoCrC tests and referential C tests with indicated minima  $(\varepsilon_m, \dot{\varepsilon}_m)$ : a)  $\dot{\varepsilon}^{vp}(\varepsilon^{vp})$  curves in CoC, CoCrC and C tests in which  $\dot{\varepsilon}_m$  was achieved at  $\sigma = 5$  MPa; b)  $\dot{\varepsilon}^{vp}(\varepsilon^{vp})$  curves in CoC and C tests in which  $\dot{\varepsilon}_m$  was achieved at  $\sigma = 7$  MPa.



Figure 11:  $\dot{\varepsilon}^{\rm vp}(\varepsilon^{\rm vp})$  curves in CoCrC tests and referential C tests at both,  $\sigma = 5$  MPa and  $\sigma = 7$  MPa, with indicated minima  $(\varepsilon_m, \dot{\varepsilon}_m)$ .

Sample/	True of test	Θ	$\sigma$	$\varepsilon_m$	$\dot{arepsilon}_m$
Test	Type of test	$^{\circ}\mathrm{C}$	MPa	%	$\%/{ m min}$
KS2	C (ref.)	-10	5	7.5	$1.1\cdot 10^{-2}$
KS9	C (ref.)	-10	7	5.8	$2.7\cdot 10^{-2}$
KS10	C (ref.)	-10	5	5.7	$5.0\cdot 10^{-3}$
KS11	C (ref.)	-10	7	5.7	$2.6\cdot 10^{-2}$
AF1	C (ref.)	-10	5	6.9	$7.3\cdot 10^{-3}$
AF2	C (ref.)	-10	5	6.5	$8.0\cdot 10^{-3}$
AF8	C (ref.)	-10	7	6.5	$3.3\cdot 10^{-2}$
AF9	C (ref.)	-10	7	6.9	$3.7\cdot 10^{-2}$
KS1	CoC	-10	$3.6 \nearrow 4 \nearrow 4.5 \nearrow 5$	9.4	$1.1\cdot 10^{-2}$
KS3	CoCrC	-10	$5 \nearrow 7 \searrow 5$	7.2	$9.2\cdot 10^{-3}$
KS4	CoC	-10	$5 \nearrow 7$	7.3	$4.8\cdot 10^{-2}$
KS7	CoCrC	-10	$5 \nearrow 7 \searrow 5$	8.3	$3.6\cdot 10^{-3}$
KS8	CoC	-10	$5 \nearrow 7$	8.3	$1.6\cdot 10^{-2}$
AF7	CoCrC	-10	$5 \nearrow 7 \searrow 5$	7.8	$1.1 \cdot 10^{-2}$

Table 5: Summary of CoC and CoCrC tests and referential C tests (excluding failed test A2 and anomalous test A6).

The strain  $\varepsilon^{\rm vp}$  is understood as the creep deformation measured from the configuration at <sup>243</sup> which the sample was frozen. The irreversible strain  $\varepsilon_m$  is defined as 1D  $\varepsilon^{\rm vp}$  accumulated <sup>244</sup> until the slowest creep rate  $\dot{\varepsilon}_m$  is achieved. This  $\varepsilon_m$  is used in the literature as a material <sup>245</sup> constant, see Sec. 2. This parameter can be evaluated for frozen KFS from all creep curves in <sup>246</sup> Secs. 4.3.1–4.3.3. The values of  $\varepsilon_m$  from all tests on frozen KFS are presented in Fig. 12. <sup>247</sup>



Figure 12: Creep strain  $\varepsilon_m$  accumulated until the slowest creep rate  $\dot{\varepsilon}_m$  as obtained from all C, CurC, CoC and CoCrC tests.

Apart from some scatter, a nearly constant (independent of  $\sigma$  and  $\Theta$ ) value of  $\varepsilon_m$  can be 248 concluded from Fig. 12. The scatter of  $\varepsilon_m$  may follow from inaccuracies in manual measurement 249 of the sample height. Mean value  $\bar{\varepsilon}_m = 7.1\%$  was found with the standard deviation of 0.9%. 250

## 4.3.5. Minimum creep rate as a material function $\dot{\varepsilon}_m(\sigma, \Theta)$ <sup>251</sup>

The slowest creep rate  $\dot{\varepsilon}_m$  in all C, CurC, CoC and CoCrC tests can be found in Fig. 13. The <sup>252</sup> function  $\dot{\varepsilon}_m(\sigma, \Theta)$  can be obtained as, e.g., the inverted  $\sigma = \sigma_\alpha + c(\Theta) \ln (\dot{\varepsilon}_m / \dot{\varepsilon}_\alpha)$ , with the <sup>253</sup> reference values  $\sigma_\alpha$  and  $\dot{\varepsilon}_\alpha$  [2, 3, 17].

4.3.6. Universal creep curve 
$$\dot{\varepsilon}^{vp}/\dot{\varepsilon}_m(\varepsilon^{vp}/\varepsilon_m)$$

Creep curves obtained from standard (uninterrupted) tests and "normalised" in the time representation  $\dot{\varepsilon}^{\rm vp}/\dot{\varepsilon}_m(t/t_m)$  are well-known in the literature, see Sec. 2. Analogous normalisation can be used for curves  $\dot{\varepsilon}^{\rm vp}(\varepsilon^{\rm vp})$ , that is,  $\dot{\varepsilon}^{\rm vp}/\dot{\varepsilon}_m(\varepsilon^{\rm vp}/\varepsilon_m)$ . In this way, one can normalise also the results from tests with interruptions.

This normalised representation is called the *universal creep curve* here. It is postulated to be 260 specific to a given type of frozen soil. Normalised curves  $\dot{\varepsilon}^{\rm vp}/\dot{\varepsilon}_m(\varepsilon^{\rm vp}/\varepsilon_m)$  from all experiments 261



Figure 13: Creep stress  $\sigma$  as function of minimum creep rate  $\dot{\varepsilon}_m$  at different temperatures  $\Theta$  as obtained from all C, CurC, CoC and CoCrC tests.

reported in Secs. 4.3.1–4.3.3 are shown in Fig. 14. These curves coincide quite well which <sup>262</sup> justifies the term *universal* creep curve for frozen KFS. <sup>263</sup>



Figure 14: Normalised creep curves  $\dot{\varepsilon}^{\rm vp}/\dot{\varepsilon}_m(\varepsilon^{\rm vp}/\varepsilon_m)$  from all C, CurC, CoC and CoCrC tests on frozen KFS.

During creep tests on frozen soil under uniaxial compression, volume changes  $\dot{V} \neq 0$  of the <sup>265</sup> sample are commonly disregarded [17]. One believes that the samples are perfectly saturated <sup>266</sup> and the substance (ice + soil particles) is volumetrically incompressible. Moreover, there are <sup>267</sup> technical difficulties in the measurement of the volume change. In the course of this research, <sup>268</sup> measurement of the volume change was undertaken and a significant volumetric creep defor-<sup>269</sup> mation of the sample could be concluded. <sup>270</sup>

To overcome complications involved in the local (contact) measurement of the horizontal displacement of the sample, one can invoke the image-based techniques, like the PIV [1, 21, 27, 28, 272 32]. It stems from fluid mechanics and allows the measurement of the displacement or velocity 273 field of a substance. In particular, the PIV can be used to measure deformation of a frozen soil 274 sample during creep. Given two 2D displacement fields on two perpendicular faces of a cubic 275 sample, the volume change can be determined. Not only the average deformation but also the 276 *distribution* of deformation can be obtained for the faces of the sample. 277

Experimental data from the PIV were obtained in the form of series of images from two cam-278 eras, one per face. The images were processed on a PC using a self-developed MATHEMAT-279 ICA package flowTrack' to find the deformation field. The MATHEMATICA internal procedure 280 ImageDisplacements[] was used. It estimates the displacement field between two subsequent 281 images for each pixel based on the so-called *dense optical flow* [10, 21]. Displacement fields 282 between the subsequent images were obtained in the spatial description and needed to be in-283 tegrated into the material description for a whole series of images. The results obtained from 284 the PIV were processed and plotted in the form of displacement fields and strain fields [23]. 285

# 4.4.1. Volumetric strain $\varepsilon_{vol}^{vp}$

Dilatancy (or contractancy) was investigated on frozen sand samples during creep under uniaxial <sup>287</sup> stress. The PIV provided a supplementary measurement of the average vertical strain but it <sup>288</sup> was essential for the average horizontal strain. It was measured for two walls of the cubic sample <sup>289</sup> as  $\varepsilon_{11}^{vp}$  and  $\varepsilon_{22}^{vp}$ , Fig. 15. In this way, the volumetric deformation  $\varepsilon_{vol}^{vp}$  could be determined. <sup>290</sup> 10 creep tests on the cubic samples (AF) from Sec. 4.3 that were conducted with the PIV are <sup>291</sup> listed in Tab. 6. Usable results from the PIV could not always be obtained for the whole test. <sup>292</sup> This was predominantly due to the so-called pixel renegades, i.e., the particles falling down <sup>293</sup>



Figure 15: Cartesian coordinate system for frozen sample during creep under uniaxial stress in tests with the PIV with two cameras.

from the sample face. This problem aggregates with increasing deformation of the sample. <sup>294</sup> The average horizontal strain  $\varepsilon_{hor}^{vp}$  obtained for both walls of the sample (as  $\varepsilon_{11}^{vp}$  and  $\varepsilon_{22}^{vp}$ ) is given <sup>295</sup> in Fig. 16 as a function of the average vertical strain,  $\varepsilon^{vp} \equiv \varepsilon_{vert}^{vp}$  (measured as  $\varepsilon_{33}^{vp}$ ). In the case <sup>296</sup> of samples AF9 and AF13,  $\varepsilon_{hor}^{vp}$  could be obtained from the PIV on one wall only and the same <sup>297</sup>  $\varepsilon_{hor}^{vp}$  was assumed for the second wall in calculation of  $\varepsilon_{vol}^{vp}$  ( $=\varepsilon_{11}^{vp} + \varepsilon_{22}^{vp} + \varepsilon_{33}^{vp}$ ). <sup>298</sup>

It can be seen in Fig. 16 that the measurements of the horizontal strain  $\varepsilon_{hor}^{vp}$  from all tests <sup>299</sup> coincide almost perfectly, independently of the testing conditions,  $\sigma$  and  $\Theta$ . The only exception <sup>300</sup> is  $\varepsilon_{hor}^{vp}$  measured on one face of sample AF7 and the most probable reason of this deviation are <sup>301</sup> the pixel renegades. <sup>302</sup>

Despite the scatter (due to the used lab technique), it can be concluded from  $\varepsilon_{\rm vol}^{\rm vp}(\varepsilon_{\rm vert}^{\rm vp})$  plots 303 given in Fig. 17 that in the primary creep stage the samples undergo initially the contractancy, 304  $\dot{\varepsilon}_{\rm vol}^{\rm vp} > 0$ . The dilatancy takes over roughly at  $\varepsilon_{\rm vert}^{\rm vp} = \frac{1}{2}\varepsilon_m$  and the accumulated compressive 305 volumetric strain  $\varepsilon_{\rm vol}^{\rm vp} > 0$  starts being reduced. The excess of the sample volume over the initial 306 value, described by  $\varepsilon_{\rm vol}^{\rm vp} < 0$ , clearly marks the beginning of the tertiary stage. 307

The contractancy/dilatancy is most likely related to the compression/expansion of air bubbles <sup>308</sup> in ice. This can be accompanied by the dissolution/nucleation and diffusion of bubbles. The <sup>309</sup> dilatancy at  $\varepsilon_{\rm vol}^{\rm vp} < 0$  is probably caused by the development and propagation of cracks within <sup>310</sup> the sample. <sup>311</sup>



Figure 16:  $\varepsilon_{\text{hor}}^{\text{vp}}(\varepsilon_{\text{vert}}^{\text{vp}})$  curves in C, CurC, CoCrC tests with indicated pairs  $(\varepsilon_m, \varepsilon_{\text{hor}}^{\text{vp}}(\varepsilon_m))$  at  $\dot{\varepsilon}_m$ .

Sample/	Turne of test	Θ	σ	$\varepsilon_m$	$\dot{\varepsilon}_m$	$\varepsilon_{\rm vol}^{\rm vp}(\varepsilon_m)$
Test	Type of test	$^{\circ}\mathrm{C}$	MPa	%	$\%/{ m min}$	%
AF1	С	-10	5	6.9	$7.3\cdot 10^{-3}$	0.2
AF2	С	-10	5	6.5	$8.0\cdot 10^{-3}$	-0.4
AF9	С	-10	7	6.9	$3.7\cdot 10^{-2}$	-0.4
AF13	С	-15	7	6.7	$2.7\cdot 10^{-2}$	-
AF14	С	-15	7	7.6	$1.2\cdot 10^{-2}$	0.4
AF17	С	-5	4	6.6	$9.0\cdot 10^{-2}$	-0.6
AF6	CurC(1 h)	-10	5	7.3	$6.2\cdot 10^{-3}$	-0.3
AF11	CurC(24 h)	-10	5	7.5	$1.1\cdot 10^{-2}$	-
AF15	CurC(7 days)	-10	5	7.4	$1.5\cdot 10^{-2}$	-
AF7	CoCrC	-10	$5 \nearrow 7 \searrow 5$	7.8	$1.1\cdot 10^{-2}$	1.0

Table 6: Summary of C, CurC and CoCrC tests extended with the PIV results.



Figure 17:  $\varepsilon_{\text{vol}}^{\text{vp}}(\varepsilon_{\text{vert}}^{\text{vp}})$  curves in C, CurC, CoCrC tests with indicated pairs  $(\varepsilon_m, \varepsilon_{\text{vol}}^{\text{vp}}(\varepsilon_m))$  at  $\dot{\varepsilon}_m$ .

A possible strain localization taking place during creep under uniaxial stress was refuted basing on the displacement and strain components obtained with the PIV as 2D fields. Time t was replaced by the average vertical strain component  $\varepsilon^{\rm vp}$ , i.e.,  $\mathbf{u}(\mathbf{X}, \varepsilon^{\rm vp})$  and  $\varepsilon^{\rm vp}(\mathbf{X}, \varepsilon^{\rm vp})$  are considered instead of  $\mathbf{u}(\mathbf{X}, t)$  and  $\varepsilon^{\rm vp}(\mathbf{X}, t)$ . Here, fields  $\mathbf{u}(\mathbf{X}, \varepsilon^{\rm vp})$  and  $\varepsilon^{\rm vp}(\mathbf{X}, \varepsilon^{\rm vp})$  are presented in the form of contour plots in Fig. 18 and Fig. 19, respectively, for one face of sample AF1 at  $\varepsilon^{\rm vp} \approx \varepsilon_m$  only. The displacement field  $\mathbf{u}(\mathbf{X}, \varepsilon^{\rm vp})$  includes the parallax error [23]. Nearly homogeneous deformation with no strain localization is observed.



Figure 18: Horizontal  $u_{\text{hor}}(\mathbf{X}, \varepsilon^{\text{vp}})$  and vertical  $u_{\text{vert}}(\mathbf{X}, \varepsilon^{\text{vp}})$  components of displacement field for one face of sample AF1 at  $\varepsilon^{\text{vp}} \approx \varepsilon_m$ .



Figure 19: Horizontal  $\varepsilon_{\text{hor}}^{\text{vp}}(\mathbf{X}, \varepsilon^{\text{vp}})$  and vertical  $\varepsilon_{\text{vert}}^{\text{vp}}(\mathbf{X}, \varepsilon^{\text{vp}})$  components of deformation field for one face of sample AF1 at  $\varepsilon^{\text{vp}} \approx \varepsilon_m$ .

Due to the common use of the ground freezing technique in tunnel construction, the stress-induced <sup>321</sup> anisotropy should be accounted for in a constitutive description of frozen soil. <sup>322</sup>

A cubic sample that creeps under compressive stress  $\sigma = \text{const}$  applied in the material direction 323  $X_3$  is schematically presented in Fig. 20a. The sample is assumed to be initially (inherently) 324 isotropic. The loading direction is always vertical regardless of the material directions:  $X_1$ , 325  $X_2$  and  $X_3$ . Before the minimum creep rate  $\dot{\varepsilon}_m$  was achieved, the sample was quickly removed 326 from the press and rotated, so that the loading direction was changed from  $X_3$  to  $X_1$ , Fig. 20b. 327 If the creep curve were regained after such operation, then the initial isotropy of the sample 328 would be preserved. However, *induced anisotropy* of frozen soil was revealed in the CA tests 329 carried out in this research. 330



Figure 20: Cubic sample during creep under stress  $\sigma = \text{const}$  applied in different material directions: a)  $X_3$ ; b)  $X_1$ ; c)  $X_2$ .

5 CA tests on the cubic samples (A and AF) at  $\sigma = 5$  MPa and  $\Theta = -10$  °C are listed in Tab. 7. The sample loaded in different material directions in a CA test is shown in Fig. 20. Two types of the CA tests were conducted and are described below.

- In the first type, CA(1), the primary creep under  $\sigma = 5$  MPa along  $X_3$  was interrupted by unloading to  $\sigma = 0$ . The same stress  $\sigma = 5$  MPa was then applied along  $X_1$  and the sample creeped until the tertiary stage.
- In the second type, CA(2), the loading direction was changed in the primary stage first  $_{337}$  from  $X_3$  to  $X_1$  and then from  $X_1$  to  $X_2$ .  $_{338}$

Vertical creep strain at which the loading direction was changed is denoted as  $\varepsilon_{\uparrow}^{\text{vp}}$ . Its values for the first  $(\varepsilon_{\uparrow}^{\text{vp}(1)})$  and for the second  $(\varepsilon_{\uparrow}^{\text{vp}(2)})$  change of the loading direction are reported in Tab. 7. Directional dependence of the creep rate in tests on samples A5, AF5 and AF16

3 CA(1) tests on samples: A5, AF5 and AF16 are considered. In these tests, the loading 344  $\sigma = 5$  MPa direction was changed from  $X_3$  to  $X_1$  at  $\varepsilon_{\uparrow}^{vp(1)} = 2.9..3.7\% < \bar{\varepsilon}_m = 7.1\%$ , see 345 Tab. 7. The samples approached the tertiary creep stage under  $\sigma = 5$  MPa applied along the 346 second loading direction. The mean value of the vertical creep strain  $\bar{\varepsilon}_m = 7.1\%$  at the slowest 347 creep rate  $\dot{\varepsilon}_m$  for the first loading direction is known from Sec. 4.3.4. 348 Creep curves,  $\varepsilon^{\rm vp}(t)$  and  $\dot{\varepsilon}^{\rm vp}(\varepsilon^{\rm vp})$ , for samples A5, AF5 and AF16 are shown in Fig. 21. A sample 349  $\sqcup$  is denoted as  $\sqcup(1)$  after the change of the loading direction, e.g., A5(1). The vertical creep 350

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strain,  $\varepsilon_{\text{vert}}^{\text{vp}} \equiv \varepsilon^{\text{vp}}$ , is  $\varepsilon_{33}^{\text{vp}}$  before and  $\varepsilon_{11}^{\text{vp}}$  after the change of the loading direction. The strain  $\varepsilon_{11}^{\rm vp}$  includes the portion from the initial creep under  $\sigma = 5$  MPa applied along 352  $X_3$ . This portion could be obtained for samples AF5 and AF16 from the PIV as the tensile 353 horizontal strain,  $\varepsilon_{\rm hor}^{\rm vp} \approx -1\%$ , as can be seen later in Fig. 23a. It turned out to be reduced 354 (almost to 0, see Fig. 21a) during application of the load in the new direction. This means that 355 the creep strain increased by  $\Delta \varepsilon_{11}^{vp} \approx 1\%$  already during the load application along the second 356 direction. The creep strain increase  $\Delta \varepsilon_{33}^{\rm vp} \approx 0$  could be measured during the loading in the first 357 direction [23]. Hence, the samples creeped significantly faster during the load application along 358 the second direction compared to the first direction which already refutes isotropy of frozen 359 soil. 360

Based on the PIV for samples AF5 and AF16, the vertical creep strain  $\varepsilon^{vp} = 0$  was assumed for 361 sample A5(1) (tested without the PIV) after the change of the loading direction. The curves 362  $\dot{\varepsilon}^{\rm vp}(\varepsilon^{\rm vp})$  from Fig. 21 are additionally plotted in Fig. 22 together with the results from three 363 similar C tests at the same  $\sigma = 5$  MPa and  $\Theta = -10$  °C. 364

It is clear in Fig. 22 that the creep rate  $\dot{\varepsilon}^{\rm vp}$  is not recovered after the change of the loading 365 direction. Hence, isotropy of frozen soil is disproven. The minimum rate  $\dot{\varepsilon}_m^{(1)}$  obtained for the 366 second loading direction is about 2 times faster than  $\dot{\varepsilon}_m$  expected for the first direction, see 367 Fig. 22. Additionally, the strain  $\varepsilon_m^{(1)} \approx 10\%$  at  $\dot{\varepsilon}_m^{(1)}$  is different from the mean value  $\bar{\varepsilon}_m = 7.1\%$ 368 at  $\dot{\varepsilon}_m$  corresponding to the first loading direction. 369

Anisotropy of frozen soil is most probably induced by changes in the microstructure during 370 the creep. Their constitutive description requires a tensorial state variable and further lab 371 investigation. 372



Figure 21: CA(1) tests A5, AF5 and AF16: a)  $\varepsilon^{\text{vp}}(t)$  curves with indicated inflections (" $t_m$ ",  $\varepsilon_m$ ) (Standing time has no meaning and hence is denoted as " $t_m$ ".); b)  $\dot{\varepsilon}^{\text{vp}}(\varepsilon^{\text{vp}})$  curves with indicated minima ( $\varepsilon_m$ ,  $\dot{\varepsilon}_m$ ).



Figure 22:  $\dot{\varepsilon}^{\rm vp}(\varepsilon^{\rm vp})$  curves in CA(1) tests A5, AF5, AF16 and the referential C tests with indicated minima  $(\varepsilon_m, \dot{\varepsilon}_m)$ .

Samples AF5 and AF16 were tested with the PIV. The dilatancy and the homogeneity of 374 deformation within the samples after the change of the loading direction were observed. Un-375 fortunately, no reliable results of PIV could be obtained for the whole tests due to the already 376 mentioned pixel renegades. In the case of sample AF5(1), the horizontal strain  $\varepsilon_{hor}^{vp}$  could be 377 gained from the PIV on one sample face only because the images of the second face were blurred. 378 After the change of the loading direction from  $X_3$  to  $X_1$  at  $\varepsilon_{\text{vert}}^{\text{vp}} = \varepsilon_{\gamma}^{\text{vp}(1)}$ , the horizontal strain 379 increase  $\Delta \varepsilon_{\text{hor}}^{\text{vp}}$  was measured via the PIV. It corresponds to the increases:  $\Delta \varepsilon_{22}^{\text{vp}}$  and  $\Delta \varepsilon_{33}^{\text{vp}}$  above 380 the values of  $\varepsilon_{22}^{\rm vp}$  and  $\varepsilon_{33}^{\rm vp}$  at  $\varepsilon_{\rm vert}^{\rm vp} = \varepsilon_{\frown}^{\rm vp(1)}$ . Analogously, the volumetric strain increase  $\Delta \varepsilon_{\rm vol}^{\rm vp}$  is 381 considered instead of the total volumetric strain  $\varepsilon_{\rm vol}^{\rm vp}$ . 382

The strain paths for creep,  $\varepsilon_{\text{hor}}^{\text{vp}}(\varepsilon_{\text{vert}}^{\text{vp}})$  and  $\varepsilon_{\text{vol}}^{\text{vp}}(\varepsilon_{\text{vert}}^{\text{vp}})$ , are presented for samples AF5 and AF16 <sup>383</sup> before and after the change of the loading direction in Figs. 23–24. These results are additionally <sup>384</sup> plotted with the ones from all other creep tests with the PIV (excluding the abnormal test AF7) <sup>385</sup> from Sec. 4.4. <sup>386</sup>

It can be seen in Fig. 24 that the samples AF5(1) and AF16(1) undergo the contractancy up <sup>387</sup> to  $\varepsilon_{\text{vert}}^{\text{vp}} \approx \frac{1}{2} \bar{\varepsilon}_m^{(1)}$ , same as samples tested without a change of the loading direction,  $\varepsilon_{\text{vert}}^{\text{vp}} \approx \frac{1}{2} \bar{\varepsilon}_m$ . <sup>388</sup> After that, the dilatancy can be observed and the sample volume exceeds the initial volume, <sup>389</sup> described by  $\varepsilon_{\text{vol}}^{\text{vp}} < 0$ , at the slowest creep rate in the case of all samples. <sup>390</sup>

The displacement components and the strain components obtained with the PIV and plotted  $_{391}$  as the fields on one wall of sample AF16(1), that is, after the change of the loading direction  $_{392}$  can be found in [23]. Distribution of the deformation is nearly homogeneous in the CA(1) tests,  $_{393}$  similarly as in the tests without a change of the loading direction.  $_{394}$ 



Figure 23:  $\varepsilon_{\text{hor}}^{\text{vp}}(\varepsilon_{\text{vert}}^{\text{vp}})$  curves with indicated pairs  $(\varepsilon_m, \varepsilon_{\text{hor}}^{\text{vp}}(\varepsilon_m))$  at  $\dot{\varepsilon}_m$ : a) in CA tests on samples AF5 and AF16; b) in CA tests on samples AF5 and AF16 and in all other creep tests with the PIV (excluding abnormal test AF7).



Figure 24:  $\varepsilon_{\text{vol}}^{\text{vp}}(\varepsilon_{\text{vert}}^{\text{vp}})$  curves with indicated pairs  $(\varepsilon_m, \varepsilon_{\text{vol}}^{\text{vp}}(\varepsilon_m))$  at  $\dot{\varepsilon}_m$ : a) in CA tests on samples AF5 and AF16; b) in CA tests on samples AF5 and AF16 and in all other creep tests with the PIV (excluding abnormal test AF7).

Sample A8 was vertically preloaded (in direction  $X_3$ ) before the freezing. This means it was <sup>397</sup> frozen with an initial effective stress state  $\sigma^{\text{eff}} = \sigma^{\text{eff}} \text{diag}(1, \approx K_0, \approx K_0)$ . The preload was <sup>398</sup> applied by tighting the screws at the top plate of the preparation equipment [23]. For this <sup>399</sup> purpose, a torque wrench was used and the axial force was assigned to the screws with the <sup>400</sup> moment M = 40 Nm. The vertical prestress  $\sigma^{\text{eff}} \approx 0.8$  MPa could be estimated using  $M = ^{401}$ 40 Nm and the parameters of the screws.

The loading direction in the case of sample A8 was changed from  $X_3$  to  $X_1$  at  $\varepsilon^{\text{vp}} = \varepsilon_{\bigcirc}^{\text{vp}(1)} = 4_{03}$ 2.6%  $< \bar{\varepsilon}_m = 7.1\%$ , similarly as in the CA(1) tests on samples A5, AF5 and AF16, see Tab. 7. 404 For this reason, the creep curves  $\dot{\varepsilon}^{\text{vp}}(\varepsilon^{\text{vp}})$  are plotted for sample A8 together with the ones for 405 samples A5, AF5 and AF16 in Fig. 25. The vertical creep strain  $\varepsilon^{\text{vp}} = 0$  was assumed after the 406 change of the loading direction based on the PIV for samples AF5 and AF16. 407

It is clear in Fig. 25 that the preload  $\sigma^{\text{eff}} \approx 0.8$  MPa in direction  $X_3$  affected the creep rate  $\dot{\varepsilon}^{\text{vp}}$ . The slower rate  $\dot{\varepsilon}^{\text{vp}}$  was obtained for the preloaded sample A8 before the change of the 409 loading direction as compared to the samples without the preloading. However, sample A8 410 demonstrates the same  $\dot{\varepsilon}^{\text{vp}}$  as samples A5, AF5 and AF16 after the change of the loading 411 direction. Unfortunately, the test on A8 was stopped before the tertiary stage was approached 412 and hence the values of the minimum creep rate  $\dot{\varepsilon}_m$  cannot be compared. 413

Systematic influence of the effective stress  $\sigma^{\text{eff}}$  on the slowest creep rate  $\dot{\varepsilon}_m$  requires further lab 414 investigation. 415

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# 4.5.2. A test with two changes of the loading direction (CA(2))

In the CA(2) test on sample A7, the loading  $\sigma = 5$  MPa direction was first changed from  $X_3$  <sup>417</sup> to  $X_1$  at  $\varepsilon^{\rm vp} = \varepsilon^{\rm vp(1)}_{\frown} = 4.9\% < \bar{\varepsilon}_m = 7.1\%$ . The sample creeped under  $\sigma = 5$  MPa until <sup>418</sup>  $\varepsilon^{\rm vp} = \varepsilon^{\rm vp(2)}_{\frown} = 5.2\% < \bar{\varepsilon}^{(1)}_m$ , wherein  $\bar{\varepsilon}^{(1)}_m \approx 10\%$  is known from the CA(1) tests. The loading <sup>419</sup> direction was then changed from  $X_1$  to  $X_2$  and the sample approached the tertiary creep under <sup>420</sup>  $\sigma = 5$  MPa applied along  $X_2$ .

The diagrams  $\dot{\varepsilon}^{\rm vp}(\varepsilon^{\rm vp})$  are shown in Fig. 26 together with the results from three CA(1) tests, <sup>422</sup> A5, AF5 and AF16. Based on the PIV for samples AF5 and AF16, the strain  $\varepsilon^{\rm vp} = 0$  was <sup>423</sup> assumed after the first change of the loading direction. Due to the lack of lab data,  $\varepsilon^{\rm vp} = 0$ 



Figure 25:  $\dot{\varepsilon}^{\rm vp}(\varepsilon^{\rm vp})$  curves in CA(1) tests A5, AF5, AF16 and A8 with indicated minima  $(\varepsilon_m, \dot{\varepsilon}_m)$ .

was assumed also after the second change of the loading direction.

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Nearly the same curves  $\dot{\varepsilon}^{\rm vp}(\varepsilon^{\rm vp})$  were obtained in the case of all samples for the first,  $X_3$ , and  $_{426}$  the second,  $X_1$ , loading direction, see Fig. 26. The rate  $\dot{\varepsilon}^{\rm vp}$  corresponding to the third loading  $_{427}$  direction,  $X_2$ , is faster than the one corresponding to the first direction,  $X_3$ , but slower than  $_{428}$  the one corresponding to the second direction,  $X_1$ . The value of strain  $\varepsilon_m^{(2)} = 5.9\%$  obtained at  $_{429}$   $\dot{\varepsilon}_m^{(2)}$  is only slightly different from the value expected for the initial loading direction  $\bar{\varepsilon}_m = 7.1\%$ .



Figure 26:  $\dot{\varepsilon}^{\rm vp}(\varepsilon^{\rm vp})$  curves in CA(2) test A7 and CA(1) tests A5, AF5 and AF16 with indicated minima ( $\varepsilon_m, \dot{\varepsilon}_m$ ).

Sample/	NT 4 • 1	Type	Θ	σ	Loading	$\varepsilon^{\mathrm{vp}}_{\curvearrowright}$	$\varepsilon_m$	$\dot{arepsilon}_m$
Test	Material	of test	$^{\circ}\mathrm{C}$	MPa	direction	%	%	$\%/{ m min}$
A5	KFS	CA(1)	-10	5	$X_3$	3.7	-	-
A5(1)	KFS	CA(1)	-10	5	$X_1$	-	10.5	$1.1\cdot 10^{-2}$
AF5	KFS	CA(1)	-10	5	$X_3$	2.9	-	-
AF5(1)	KFS	CA(1)	-10	5	$X_1$	-	10.5	$1.2\cdot 10^{-2}$
AF16	KFS	CA(1)	-10	5	$X_3$	3.2	-	-
AF16(1)	KFS	CA(1)	-10	5	$X_1$	-	10.4	$1.6\cdot 10^{-2}$
A8	KFS	CA(1)	-10	5	$X_3$	2.6	-	-
A8(1)	KFS	CA(1)	-10	5	$X_1$	-	-	-
A7	KFS	CA(2)	-10	5	$X_3$	4.9	-	-
A7(1)	KFS	CA(2)	-10	5	$X_1$	5.2	-	-
A7(2)	KFS	CA(2)	-10	5	$X_2$	-	5.9	$9.1\cdot 10^{-3}$

Table 7: Summary of CA tests.

#### 5. Creep tests under isotropic compression

Observations on the purely volumetric creep of ice are possible in unsaturated samples [12]. It 432 was shown that the volumetric creep of ice under isotropic pressure is due to the presence of air 433 bubbles, Fig. 27. Unfortunately, there is lack of experimental results from the literature in the 434 case of frozen soil. Purely volumetric creep of frozen soil is possible, if air bubbles are present. 435 To the authors' knowledge, the volumetric deformation under isotropic stress is a rarely studied 436 aspect of the constitutive description of creep in frozen soil. 437



Figure 27: Volumetric strain  $\varepsilon_{\text{vol}}^{\text{vp}}$  as function of time t for pure ice with air bubbles under isotropic pressure p = const applied at t = 0.

The volumetric creep of frozen sand was investigated under isotropic pressure in the course of <sup>438</sup> this research [23, 35]. Samples were tested in a pressure vessel. Isotropic stress was applied on <sup>439</sup> the sample through the cell fluid (hydraulic oil). Volumetric strain of the sample was determined <sup>440</sup> by measuring the relaxation of the pressure in cell. <sup>441</sup>

No acceleration of the creep rate, let alone the three stages of creep: primary, secondary and tertiary, were expected in the case of isotropic loading. It was attempted to verify and quantify the following hypotheses known from the tests on pure ice with air bubbles [12].

- Creep deformation during a quick load application can be neglected.
- No influence of the unfrozen water inside the frozen sample (around the grains) is taken 446 into account. This is justified by relatively low values of the unfrozen water content 447 μ<sup>w</sup> ≤ 1% in frozen sands [20].
- Within the first couple of hours, creep is mainly due to the compression of air bubbles. The  $_{449}$  initial atmospheric pressure  $p^{\text{atm}}$  inside a bubble increases up to the target pressure p and  $_{450}$

the volume  $V^{a}$  of air bubbles decreases according to the Boyle-Mariotte law  $pV^{a} = \text{const.}$  451

- Next, the compressed air bubbles are dissolved and diffuse slowly in the ice according to 452 the Henry's law. For sufficiently high pressure, no bubbles will eventually be left which 453 may take a few days.
- Finally, the frozen sand sample consists only of the almost incompressible substance (no 455 air bubbles) and the volumetric deformation reaches asymptotically a limit. 456

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## 5.1. Tested material, sample preparation and experimental procedures

Cylindrical samples with the diameter of 5 cm and the height of 10 cm were obtained by freezing 458 KFS with different saturation. The size of samples was limited by the available testing device. 459 Tests were conducted in the relaxation chamber placed in the cold room. 460

## 5.2. Processing of data

Temperature recordings and displacement of the piston into/out of the pressure vessel were <sup>462</sup> provided by the data logger of the testing device. Values of pressure were read from the images <sup>463</sup> of the manometer and manually appended to the experimental data. Raw lab measurements <sup>464</sup> required correction for air bubbles in cell fluid. This correction was evaluated experimentally <sup>465</sup> [23].

### 5.3. Purely volumetric creep

Samples were investigated at  $\Theta = -10$  °C in the relaxation chamber filled with the hydraulic 468 oil. The pressure  $p_0 = 10$  MPa was applied inside the vessel and the visco-plastic volumetric 469 strain  $\varepsilon_{\rm vol}^{\rm vp}$  of the samples was obtained from the relaxation of the cell pressure,  $\dot{p} < 0$ . 470 3 tests on samples: P1, P2 and P7 with different values of the degree of saturation S are 471 considered, see Tab. 8. Elastic response of the samples with the sample bulk modulus K = const472 was assumed during application of the load. Two steps of the load application were used. In 473 the first step, the pressure was applied from  $p = p^{\text{atm}}$  to p = 8 MPa using the oil pump. In 474 the second step, the pressure was increased from p = 8 MPa to  $p = p_0 = 10$  MPa by screwing 475 of the piston. The constant bulk modulus K = 5.5 GPa [16] was used for the pressure range 476  $p = p^{\text{atm}}$ ..8 MPa. The values of K (secant) for p = 8..10 MPa are given in Tab. 8. They were 477 calculated for each sample by subtracting the reference results from the test on a steel dummy 478 sample conducted for the correction for air bubbles in oil, see [23].

The value of K increases with the degree of saturation S of the sample as it is observed in 480 unsaturated soils with water. However, they are unrealistically low. This is probably due to 481 a larger amount of the bubbles present in the oil in the considered tests than in the test on the 482 dummy sample. Hence, all results obtained from the CI tests are fraught by the error due to 483 the air bubbles in cell fluid. 484

Table 8: Summary of CI tests.						
Sample/	S	$K$ for $p=810~\mathrm{MPa}$				
Test	-	MPa				
P1	0.77	134				
P2	0.82	416				
$\mathbf{P7}$	0.95	749				

The purely volumetric creep deformation of the samples is shown as a time function  $\varepsilon_{\rm vol}^{\rm vp}(t)$  <sup>485</sup> in Fig. 28. It can be seen that initially the samples creeped fast with a nearly constant rate <sup>486</sup>  $\dot{\varepsilon}_{\rm vol} \approx \text{const.}$  Then, the creep slowed down and  $\varepsilon_{\rm vol}^{\rm vp}$  achieved asymptotically a final constant <sup>487</sup> value  $\varepsilon_{\rm vol\,max}$ . These observations are similar to the ones for pure ice [12]. The values of  $\varepsilon_{\rm vol\,max}$  <sup>488</sup> increase with the decreasing degree of saturation *S*.



Figure 28:  $\varepsilon_{\text{vol}}^{\text{vp}}(t)$  in the CI tests.

The physical interpretation of the purely volumetric creep of frozen soil pertains solely to the 490 case of isolated air bubbles in the pore ice and corresponds roughly to the degree of saturation 491  $S \gtrsim 0.97$  [23]. Samples P1 and P2 with  $S \ll 0.97$  have to be disregarded. Only sample P7 492 with S = 0.95 included solely isolated air bubbles and can be evaluated. 493 Note that a peculiar behaviour of sample P7 can be observed in Fig. 28. After the initial increase, the volumetric strain  $\varepsilon_{\rm vol}^{\rm vp}$  decreased slightly before the final value  $\varepsilon_{\rm vol\,max}$  was established. This could be caused by the relaxation of the cell pressure. The volumetric deformation  $\varepsilon_{\rm vol}^{\rm vp}$  and the relaxation of the bubbles (both in the sample and cell fluid) was initially dictated by  $p_0$ . The reduction of the bubbles (both in the sample and cell fluid) resulted in the relaxation  $\dot{p} < 0$  but a certain amount of the bubbles was already dissolved in the ice. According to the Henry's law, less moles of the free air can be dissolved under the decreased p. Thus, the bubbles might have nucleated due to  $\dot{p} < 0$ .

Volumetric creep is due to the compression (or expansion) of air bubbles in frozen sample alone, <sup>501</sup> similarly as it is in the case of pure ice [12]. Phenomena like dissolution, nucleation and diffusion <sup>502</sup> of air bubbles in ice are rather negligible (about 250 times smaller than in water judging by <sup>503</sup> the Henry constant [11]). <sup>504</sup>

The purely volumetric and oedometric creep of frozen soil has been recently further investigated <sup>505</sup> in the course of a master thesis at IBF, KIT [36]. <sup>506</sup>

## 6. Conclusions

Current evaluation of the creep deformation of artificially frozen soil should be revised. Constitutive models from the literature for frozen soil use explicit time functions. Direct time dependence depletes a constitutive description of the autonomity and generality. Application of the available models is thus restricted to uninterrupted creep only. A sound constitutive background for creep of frozen soil is of practical importance for the ground freezing technology. Formulation of an improved model requires novel lab evidence. For this purpose, different aspects of the creep of frozen soil were examined in the course of this research.

Frozen sand samples were investigated under uniaxial compression. Creep rate turned out to recover after any kind of interruptions, like unloadings or overloadings. In this way, a universal creep curve was established for frozen Karlsruhe Fine Sand.

Tests on cubic samples were conducted with the PIV. It allowed the quantification of the volumetric changes during creep under uniaxial stress. Contractancy and dilatancy of the sample were observed. Moreover, the distribution of deformation within the sample was judged from the 2D deformation fields on sample walls. No strain localization during creep could be observed.

Induced anisotropy of frozen soil was revealed in the tests with changes of the loading direction. 523 Cubic sample under uniaxial stress was unloaded, rotated by  $90^\circ$  and reloaded back to the 524 previous stress. Creep rate prior to the change of the loading direction was not regained. 525 Additionally, the creep tests under isotropic compression were carried out. Purely volumetric 526 creep of frozen soil was shown to be due to the presence of air bubbles alone. 527 A refined material description is currently being developed. Novel model MROZON for creep of 528 frozen soil will account for the effective stress in soil skeleton and in ice. 529

Declarations	530
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Availability of data and material	535
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Code availability	537
The relevant packages for the algebra program MATHEMATICA are available on an e-mail request.	538
Authors' contributions	539
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References	541
[1] Chupin O, Rechenmacher A, Abedi S (2011) Finite strain analysis of nonuniform defor-	542
mation inside shear bands in sands. International Journal for Numerical and Analytical	543
Methods in Geomechanics 36(14):1651–1666, DOI 10.1002/nag.1071	544

[2] Cudmani R (2006) An elastic-viscoplastic model for frozen soils. In: Triantafyllidis T (ed) 545 Numerical Modelling of Construction Processes in Geotechnical Engineering for Urban 546 Environment, Taylor & Francis Group, pp 177–183 547

[3]	Cudmani R, Yan W, Schindler U (2022) A constitutive model for the simulation of temperature-, stress- and rate-dependent behaviour of frozen granular soils. Géotechnique pp 1–36, DOI 10.1680/jgeot.21.00012	548 549 550
[4]	Domaschuk L, Shields D, Rahman M (1991) A model for attenuating creep of frozen sand. Cold Regions Science and Technology 19:145–161	551 552
[5]	Eckardt H (1979) Creep behaviour of frozen soils in uniaxial compression tests. Engineering Geology 13(1):185–195, DOI 10.1016/0013-7952(79)90031-0	553 554
[6]	Eckardt H (1979) Tragverhalten gefrorener erdkörper. PhD thesis, Institut für Boden- und Felsmechanik, Universität Fridericiana in Karlsruhe, Heft Nr. 81	555 556
[7]	Eckardt H (1982) Creep tests with frozen soils under uniaxial tension and uniaxial com- pression. In: Proceedings of the 4th Canadian Permafrost Conference, pp 394–405	557 558
[8]	Fender K (2017) Low probability – high impact. Rail Engineer pp 34–38	559
[9]	Fuentes Lacouture W (2014) Contributions in mechanical modelling of fill materials. Veröffentlichungen des IBF/KIT, Karlsruher Institut für Technologie, Heft 179	560 561
[10]	Hassner T, Liu C (2016) Dense Image Correspondences for Computer Vision. Springer, Switzerland	562 563
[11]	Ikeda-Fukazawa T, Fukumizu K, Kawamura K, Aoki S, Nakazawa T, Hondoh T (2005) Effects of molecular diffusion on trapped gas composition in polar ice cores. Earth and Planetary Science Letters 229(3):183–192, DOI 10.1016/j.epsl.2004.11.011	564 565 566
[12]	Jones S, Johari G (1977) Effect of hydrostatic pressure on air bubbles in ice. In: Isotopes and Impurities in Snow and Ice, IAHS Redbooks, Gentbrugge, Belgium, vol 118, pp 23–28	567 568
[13]	Knittel L (2020) Verhalten granularer böden unter mehrdimensionaler zyklischer beanspruchung. Veröffentlichungen des IBF/KIT, Karlsruher Institut für Technologie, Heft 188	569 570 571
[14]	Liu Z, Yu X (2011) Coupled thermo-hydro-mechanical model for porous materials under frost action: Theory and implementation. Acta Geotechnica 6:51–65, DOI 10.1007/s11440-011-0135-6	572 573 574

10.1007/s11440-015-0391-y 577 [16] Merz K, Vrettos C (2015) Aktuelle Forschung in der Bodenmechanik, chap Materialverhal-578 ten von gefrorenem Sand aus Triaxialversuchen an kubischen Proben, pp 101–117. DOI 579 10.1007/978-3-662-45991-1\_6 580 [17] Orth W (1986) Gefrorener Sand als Werkstoff: Elementversuche und Materialmodell. PhD 581 thesis, Institut für Boden- und Felsmechanik, Universität Fridericiana in Karlsruhe, Heft 582 Nr. 100 583 [18] Orth W (2018) Grundbau-Taschenbuch Teil 2, John Wiley & Sons, chap 2.4 Boden-584 vereisung, pp 299–373. DOI 10.1002/9783433607312.ch4 585 [19] Orth W, Meissner H (1982) Long-term creep of frozen soil in uniaxial and triaxial tests. 586 In: Proc. 3rdn Int. Symp. on Ground Freezing, Hanover, N.H., USA 587 [20] Osterkamp T, Burn C (2015) Cryosphere permafrost. In: North G, Pyle J, Zhang F (eds) 588 Encyclopedia of Atmospheric Sciences (Second Edition), second edition edn, Academic 589 Press, Oxford, pp 208–216, DOI 10.1016/B978-0-12-382225-3.00311-X 590 [21] Srokosz P, Bujko M, Bocheńska M, Ossowski R (2021) Optical flow method for measuring 591 deformation of soil specimen subjected to torsional shearing. Measurement 174:109064, 592 DOI 10.1016/j.measurement.2021.109064 593 [22] Staroszczyk R (2019) Ice Mechanics for Geophysical and Civil Engineering Applications. 594

[15] Ma L, Qi J, Yu F, Yao X (2015) Experimental study on variability in mechanical properties

of a frozen sand as determined in triaxial compression tests. Acta Geotechnica 11, DOI

575

576

- Springer, Switzerland
   595

   [23] Staszewska K (2022) Towards a constitutive description of creep in frozen soils. Disserta 596
- [23] Staszewska K (2022) Towards a constitutive description of creep in frozen soils. Dissertation, Gdańsk University of Technology, DOI 10.13140/RG.2.2.35977.11364
- [24] Šuklje L (1957) The analysis of the consolidation process by the isotaches method. In: 598
   Proceedings 4th International Conference on Soil Mechanics and Foundation Engineering, 599
   Butterworths Scientific Publications, pp 200–206

- [25] Ting J (1981) The creep of frozen sands: Qualitative and quantitative models. Mas-601 sachusetts Inst of Tech Report 602
- [26] Ting J (1983) On the nature of the minimum creep rate time correlation for soil, ice, 603 and frozen soil. Canadian Geotechnical Journal 20:176–182, DOI 10.1139/t83-017 604
- 27 Vogelsang J (2017)Untersuchungen zu den mechanismen der pfahlrammung. 605 Veröffentlichungen des IBF/KIT, Karlsruher Institut für Technologie, Heft 182 606
- [28] White D, Take W, Bolton M (2003) Soil deformation measurement using parti-607 cle image velocimetry (piv) and photogrammetry. Géotechnique 53(7):619–631, DOI 608 10.1680/geot.2003.53.7.619609
- [29] Wichtmann T (2016) Soil behaviour under cyclic loading experimental observations, con-610 stitutive description and applications. Veröffentlichungen des IBF/KIT, Karlsruher Institut 611 für Technologie, Heft Nr 181 (habilitation) 612
- [30] Wolfram Research Inc (2021) Mathematica
- [31] Xu X, Wang Y, Zhenhua Y, Zhang H (2017) Effect of temperature and strain rate on me-614 chanical characteristics and constitutive model of frozen helin loess. Cold Regions Science 615 and Technology 136, DOI 10.1016/j.coldregions.2017.01.010 616
- [32] Yao X, Wang W, Zhang M, Wang S, Wang L (2021) Strain localization of a frozen sand 617 under different test conditions. Cold Regions Science and Technology 183:103226, DOI 618 10.1016/j.coldregions.2021.103226 619
- Η (2015)Zur gebrauchtauglichkeit gründungen für 33 Zachert von offschore-620 windenergieanlagen. Veröffentlichungen des IBF/KIT, Karlsruher Institut für Technologie, 621 Heft 180 622
- [34] Zhou G, Zhou Y, Hu K, Wang Y, Shang X (2018) Separate-ice frost heave model for one-623 dimensional soil freezing process. Acta Geotechnica 13, DOI 10.1007/s11440-017-0579-4 624
- [35] Zürn J (2021) Volumetrisches Kriechverhalten in gefrorenem Sand. Karlsruher Institut für 625 Technologie 626

[36] Zürn J (2022) Volumetrisches und ödometrisches Kriechverhalten in gefrorenem Sand. 627
 Master's thesis, Karlsruher Institut für Technologie 628