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# A Laboratory Study on the Shear Strength Behavior of Two Till Deposits from Northern Germany

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**Abstract:** This paper presents the findings of a laboratory study of the shear strength and yielding behavior of two glacial till soil deposits from the area of Heiligenhafen, northern Germany. The tests were conducted on reconstituted forms of the soils using a triaxial cell capable of controlling the temperature of the specimens. The experimental program included a series of multi-stage consolidated drained (CD) compression triaxial tests at temperature ranges between 20 and 60 °C. For the temperature range considered in this study, a mild reduction in the effective friction angle of the two till soils of less than 1° was observed due to an increase in temperature from 20 to 60 °C. All the results were carefully assessed in view of the intrinsic soil behavior and fabric, and existing trends are highlighted. The findings of this study provide valuable insights into the shearing properties of till deposits, and can contribute to the enhancement of existing soil constitutive models as well as the development of new models that are particularly suited to the behavior of glacial tills under elevated temperatures.

**Keywords:** glacial tills; triaxial testing; shear strength; friction angle



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## 1. Introduction

Glacial deposits are important for soil mechanics and geotechnical engineers working with soil deposits in areas of northern Europe, North American and northern Asia, because large portions of these areas were historically covered with ice, which led to the formation of various till deposits. Tills are mainly classified as a poorly graded mixture of gravel or cobble-sized boulders, sand, silt, and clay materials deposited by ice glaciers [1]. The sedimentary glacial deposits generally show a wide range of variations, from weak plastic clay tills to highly dense non-plastic tills. This high degree of variation is accredited to factors such as variations in the composing minerals, the modes by which the minerals were integrated in the ice, and by their modes of transportation and deposition, etc. [2].

The glacial till deposits found in northern Germany were mainly formed due to ice advances from Scandinavia via the Baltic depression to the south [3,4]. Determination of the shear strength behavior of these soils enables the use of these glacial deposits for geotechnical and engineering purposes as the foundation or media of support for structures built upon them. Furthermore, the geomechanical properties of till soils are generally not clearly defined in the literature, because they cannot be classified in the traditional categories of coarse- or fine-grained soils and do not conform to the commonly known soil depositional and mechanical models [2,5]. Moreover, existing work on the shear strength properties, and in particular the effect of temperature, on the behavior of glacial till deposits is limited, despite the large areas covered by such deposits.

On this basis, the research presented in this paper focuses on providing new information on the experimental temperature-dependent shear strength and yielding behavior of two glacial till soils from northern Germany to supplement the existing body of work on the geomechanical behavior of till deposits. For this purpose, multi-stage consolidated drained (CD) compression triaxial tests were performed on the till soils at temperature ranges between 20 and 60 °C using a triaxial device capable of applying controlled temperature conditions to the specimens.

Assessing the effect of temperature on the shear strength behavior or the thermomechanical behavior of soils is necessary for many engineering applications such as seasonal heat energy storage, radioactive waste disposal, the extraction of hydrocarbons from oil sands, freezing and thawing soil processes, etc. Several experimental and modeling studies were performed in the past with regards to the thermomechanical behavior of clayey soils at varying temperature levels [6–9]. Other studies focused on investigating the thermo-hydro-mechanical behavior of saturated fine-grained soils under elevated temperatures in view of the safe design of various applications such as oil and gas pipelines, ground thermal energy storage, underground high voltage electrical cables, and nuclear waste disposal barriers [10–13].

Abuel-Naga et al. [8] performed drained compression triaxial shear tests on a soft Bangkok Clay at temperatures between 25 and 90 °C. Their findings showed that the samples of the clay soil sheared at higher temperature values exhibited a higher peak deviatoric stress values. Furthermore, for the soil sheared at normally consolidated conditions, a strain hardening behavior was seen at room temperature, whereas a strain softening behavior was exhibited at elevated temperatures.

Uchaipichat and Khalili [14] performed experimental studies on the thermomechanical behavior of an unsaturated laboratory compacted silt at temperatures between 25 and 60 °C using modified triaxial equipment in temperature- and suction-controlled conditions. The findings of their consolidated drained conventional compression shear tests showed a reduction in the shear strength of the soil (expressed in the form of deviatoric stress at failure) with an increase in soil temperature from 25 to 60 °C. The effective cell pressures used for their studies were 50, 100, and 150 kPa. A comprehensive and detailed review of thermomechanical engineering behavior of soils at elevated temperatures is presented elsewhere [15].

Most of the studies showed a considerable dependence of the mechanical performance of the investigated soils at medium temperature. Several publications on the thermal behavior of fine-grained soils have shown a reduction in soil volume (compaction) with an increase in temperature under drained conditions [16–18]. Other studies [19–21] have shown that normally consolidated clays show thermal contractive behavior, while overconsolidated clays can show thermal dilatant behavior [7]. These findings strongly suggest that for loose and normally consolidated fine-grained soils, heating produces a thermal contractive behavior (soil volumetric compaction), which can result in the increase in the shear strength of the soils, whereas for dense or overconsolidated soils, heating produces a thermal dilatant behavior (soil volumetric expansion), which can then produce a decrease in the shear strength capacity of the soils.

## 2. Experimental Program

### *2.1. Tested Soils*

Two naturally occurring glacial till soils from the Hohe Ufer cliff of Heiligenhafen (Figure 1) along the southern Baltic Sea coast in East Holstein, northern Germany, were used for the laboratory study. The first till soil (Figure 2a), with a relatively younger age "oberer Geschiebemergel, weichselzeitlich (Weichselian)" is referred to in this study as "oM". This till deposit is, however, a variation of or slightly different from the "oberer Geschiebemergel" till deposit mentioned in the literature by Stephan [22]. The typical "oberer Geschiebemergel" till in the literature is also commonly known as "Upper Till" [23]. The second till soil (Figure 2b), with a comparatively older age or deposited earlier than the oM till is referred to in this study as "mittlerer Geschiebemergel, saalezeitlich (Saalian)", or 'mM'. This till deposit is also known in the literature as "Middle Till". The abbreviations and naming of the till soils used in this study follow, or are modifications of, previous studies [22].

(**a**) (**b**)

**Figure 1.** Sampling locations of the till soils in Heiligenhafen area, northern Germany: (**a**) "oberer Geschiebemergel, weichselzeitlich (Weichselian)" (oM) glacial till deposit, location 54°22′55.0″ N 10°56′12.9″ E (54.381951, 10.936909); (**b**) "mittlerer Geschiebemergel, saalezeitlich (Saalian)" (mM) glacial till deposit, location 54°22′54.6″ N 10°56′06.4″ E (54.381833, 10.935111).

(**a**) (**b**)

**Figure 2.** Samples of the glacial till soils: (**a**) oM; (**b**) mM.

Overall, three Pleistocene tills could be distinguished in the coastal cliff section near Heiligenhafen based on their structural and petrographic properties [23]. However, in our study, we were able to collect till samples from the upper two till layers (i.e., a variation of the Upper Till layer and from the Middle Till), and could not obtain samples from the "Lower Till" layer (which is the oldest of all three and referred to in the literature as "unterer Geschiebemergel, saalezeitlich (Saalian)" or "uM"), because this till deposit was too hard to be penetrated by our tools for the collection of undisturbed samples for field density analysis. Stephan [24] also identified a fourth (lowermost) till, first mentioned in 1992, below the uM or Lower Till layer; however, we did not attempt to collect samples from this layer during our field visits.

Table 1 presents a summary of the obtained physical properties of the soils, in accordance with ASTM D420-D5876 [25]. The particle size distributions and X-ray diffraction (XRD) mineralogical analysis results of the till soils are shown in Figures 3 and 4, respectively.

The particle size gradation of the till soils was obtained by wet-sieving the soils using sieves arranged in the order of 16, 8, 4, 2, 1, 0.5, 0.25, 0.125 and 0.063 mm, and a hydrometer analysis (sedimentation process) was used to obtain the gradation for particles whose median diameters were smaller than 0.063 mm, which included silt and clay size particles [26]. We attempted to obtain the Atterberg limits (liquid limit, plastic limit, and plasticity index) of the soils following the standard criteria; however, as expected, the till soils did not exhibit properties of fine-grained soils, and lacked sufficient quantities of clay and silt-sized particles to acquire considerable plasticity, and hence the measurement of

Atterberg limits could not be achieved. Moreover, the soils did not fall into any of the pure-categories of coarse- and fine-grained soils as depicted in the Unified Soil Classification System (USCS), and hence are classified using dual symbols as shown in Table 1.

**Table 1.** Geotechnical properties of the glacial till soils obtained through measurements at Kiel University.

| Properties | oM | mM |
|---|---|---|
| Gravel, >2 mm (wt.%) | 2.85 | 4.72 |
| Sand, 0.063–2 mm (wt.%) | 50.98 | 57.08 |
| Silt, 0.002–0.063 mm (wt.%) | 43.20 | 37.39 |
| Clay, <0.002 mm (wt.%) | 2.97 | 0.81 |
| Porosity $n$ (-) | 0.281 | 0.258 |
| Solids specific gravity $G_s$ (-) | 2.650 | 2.696 |
| Bulk dry density $\rho_d$ (kg m$^{-3}$) | 1.905 | 2.000 |
| Natural gravimetric water content $w_n$ (%) | 14.68 | 9.52 |
| Liquid limit $L_L$ (%) | NA [1] | NA [1] |
| Plastic limit $P_L$ (%) | NA [1] | NA [1] |
| Plasticity index $P_I$ (%) | NP [2] | NP [2] |
| Grain diameter at 10% passing $D_{10}$ (mm) | 0.0085 | 0.014 |
| Grain diameter at 50% passing $D_{50}$ (mm) | 0.070 | 0.100 |
| Coefficient of uniformity $C_u$ (-) | 10.588 | 10.000 |
| Coefficient of curvature $C_c$ (-) | 2.092 | 1.127 |
| Lime content (%) | 6.67 | 12.56 |
| Unified soil classification system (USCS) | ML or CL [3] | SM or SC [4] |

[1] not available, standard criteria not satisfied. [2] non-plastic. [3] silt or clay of low plasticity. [4] silty or clayey sand.

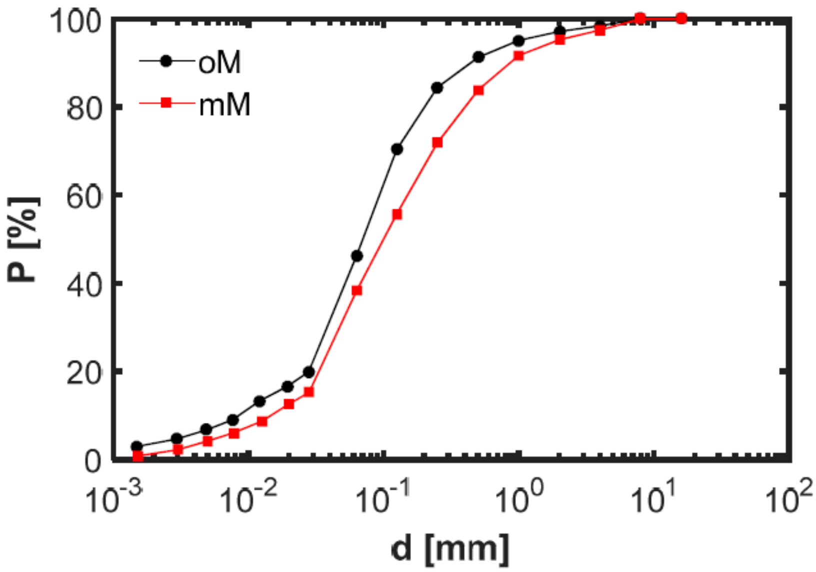



**Figure 3.** Grain size distributions (percent passing $P$ vs. grain diameter $d$ plots) of the two till soils.

For the XRD plots of Figure 4, only the dominant (minerals with a significant comparative fraction of the total soil grain mass or volume) are noted, and hence other mineral forms existing in the soil structure at low or negligible fractions have not been included. On this basis, the particle grain skeletons of both oM and mM tills heavily comprised quartz and calcite minerals, with till mM also having an additional significant presence of albite (a member of the plagioclase feldspar group) minerals.

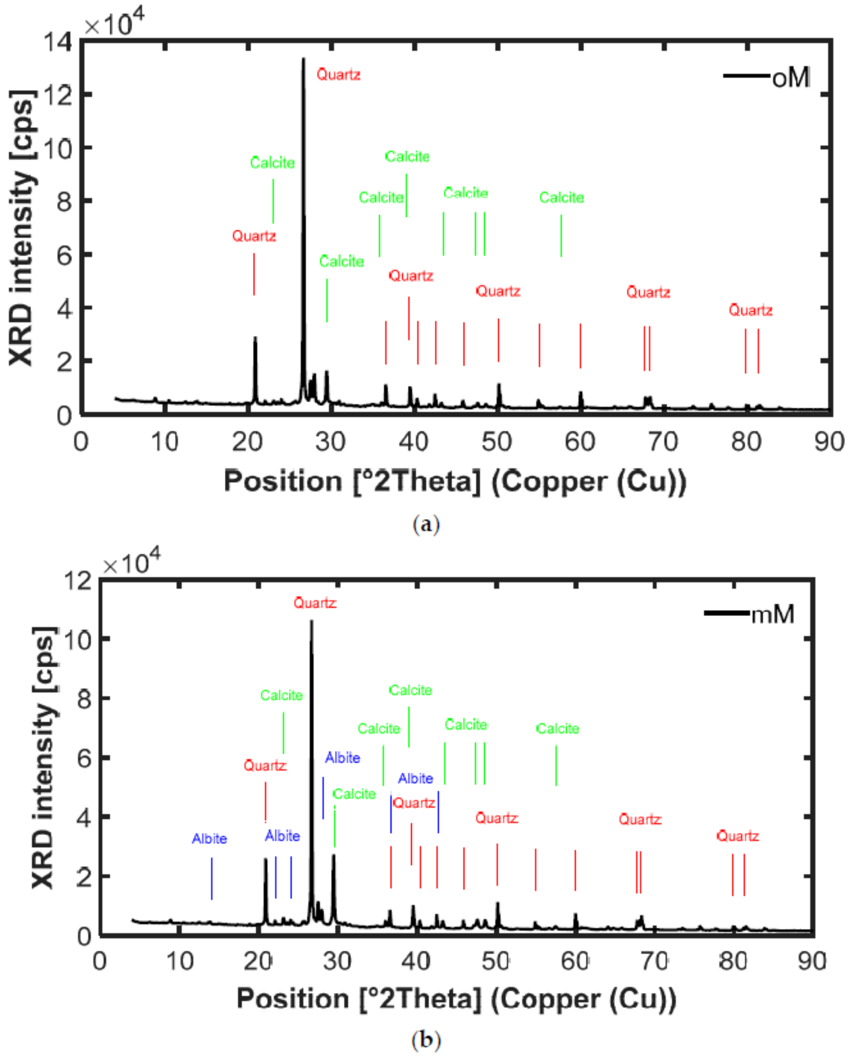



**Figure 4.** XRD plots of the till soils: (**a**) oM; (**b**) mM.

## *2.2. Equipment Used*

The shear strength behavior of the till soils was studied experimentally using a modified triaxial testing device capable of controlling the sample temperature (Figures 5 and 6). The test apparatus consisted of a triaxial cell with controlled temperature conditions (Figure 6), a UL-60 loading machine equipped with a high accuracy KAS-E/D-type load cell capable of applying deviatoric stresses with a maximum force limit of 60 kN (Figure 5b), a TRS-0050 linear transducer (with a defined range of 50 mm and repeatability of 2 µm) for measuring axial specimen deformation, a double channel volume–pressure-controller (VPC-D) 250/20 cell pressure and pore-water (back-pressure) application system (with a volumetric capacity of each piston of 250 mL and maximum pressure limit of 20 bar or 2000 kPa), a PR-25Y type pore-gas pressure sensor (with a capacity of 10 bar or 1000 kPa) for measuring pore-water pressure of the specimen, a Huber Ministat 125 Pilot ONE heat pump for controlling the temperature of the triaxial cell water and specimen via a circulating fluid (glycol + distilled water), and a PC control and data logger units for system control and data recording (Figure 5a).

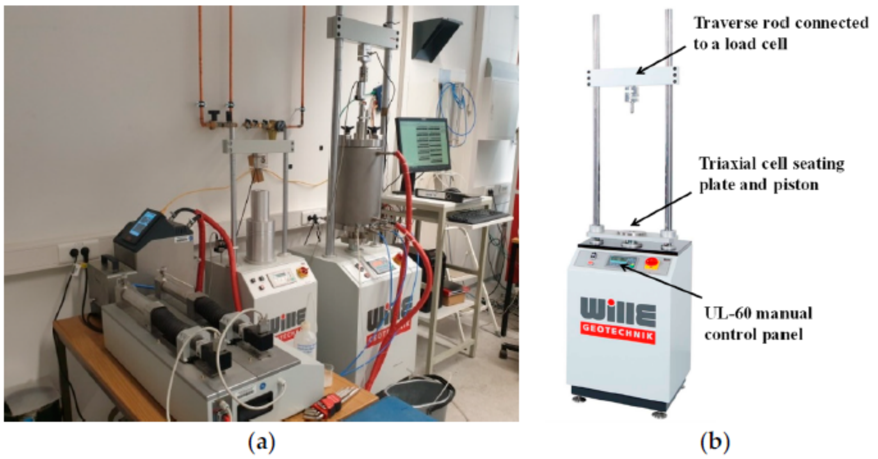



**Figure 5.** Triaxial testing apparatus used in testing the till soils: (**a**) complete set-up; (**b**) UL-60 loading machine.

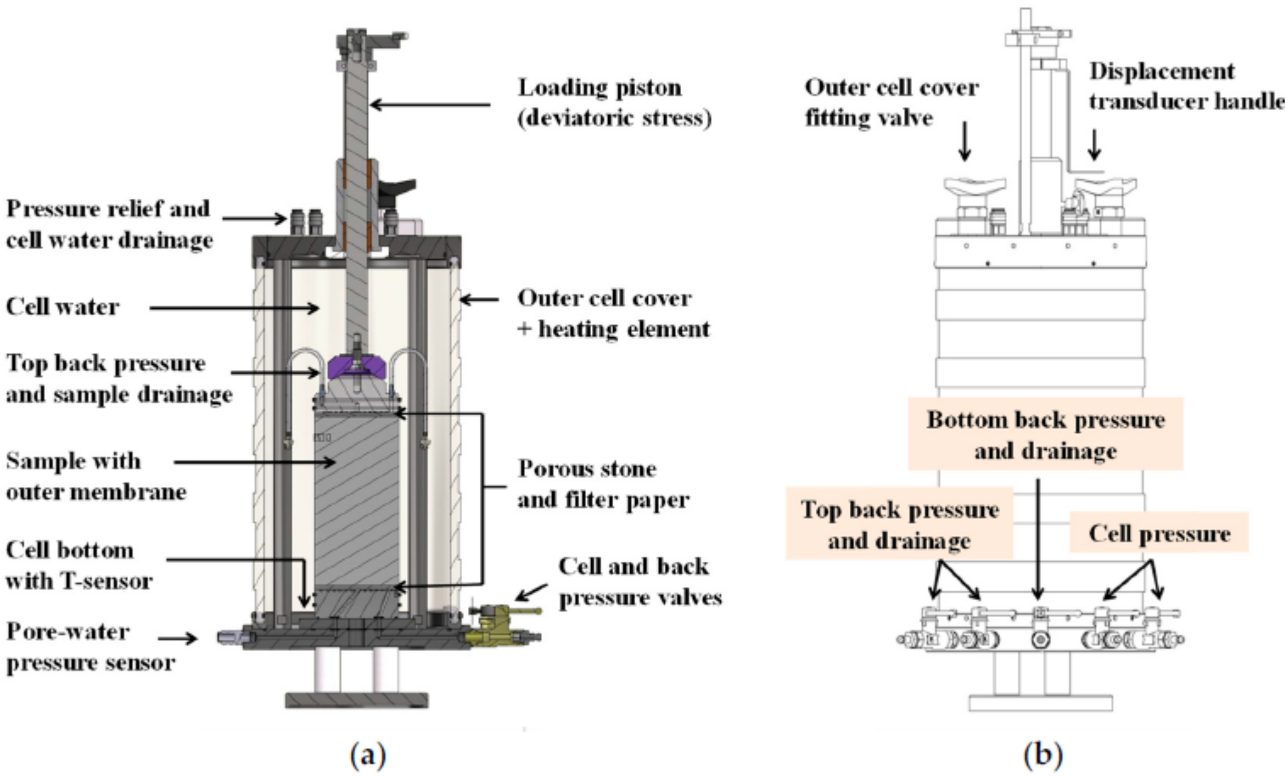



**Figure 6.** Schematic representations of the triaxial cell used in the study (sample size not to scale): (**a**) inner sectional view; (**b**) front view.

## 2.3. Experimental Procedure

The till samples for the triaxial testing were prepared under remolded and lab compacted conditions in their natural field moisture state, with dimensions of diameter 50 mm and a height of 100 mm. This satisfies the standard sample preparation criteria according to ASTM D7181 [27], where a minimum diameter of sample of 33 mm and an average-height-to-average-diameter (H/D) ratio between 2 and 2.5 is recommended. Extra care was taken to ensure that the bulk density was homogeneous throughout the specimen volume, and the bottom and top faces were made flat to ensure a uniform distribution of the applied deviatoric stress. The bulk density used for preparing the remolded samples was calculated using undisturbed till specimens obtained from the sampling locations to ensure that actual field (density) conditions were met.

Prior to the start of each test, the water compartments underneath the bottom or base pedestal (the back-pressure or bottom drainage line), the top loading cap, the pore-water pressure sensor line from the back of the cell, and the two top drainage and back-pressure lines were flushed with de-aired water to remove all entrapped air in the system. Standard rubber membranes were used to contain the samples laterally, and after placing the specimen in position, two pairs of O-rings were used to fit the rubber membranes with each of the bottom pedestal and the top cap to ensure the separation of the cell- and back-pressures applied to the samples.

After preparing the sample and filling the triaxial cell with water, and prior to the start of the triaxial tests, the cell water temperature was heated to the desired value using the heating pump, and sufficient time was allotted for the stabilization of temperature in the samples. In order to avoid an increase in water pressure inside the closed cell system due to the expansion of the cell water during heating, an external VPC water pressure control and application system was connected to the cell to regulate the water pressure in the cell by allowing extra water to be removed from the cell to the VPC pump throughout the duration of the heating process. Once the temperature and expansion of the water in the cell were stabilized, the VPC pump was removed, and the triaxial tests were started.

The CD triaxial compression tests (i.e., $\sigma_1 > \sigma_2 = \sigma_3$) were performed at confining pressures of 100–300 kPa and temperatures between 20 and 60 °C using the multi-stage or pressure-stepping compression technique [28–30]. These stresses were selected based on the existing site overburden pressures on the till layers from the Hohe Ufer cliff of Heiligenhafen. At Hohe Ufer, the uppermost till (oM) is continuously exposed along the top of the cliff and has a thickness of up to 2 m, whereas the lower tills (mM and uM) are discontinuously exposed with thicknesses varying from a few to tens of meters [23].

With pressure-stepping experiments, the peak strength of the soil at three confining stresses and isothermal conditions can be obtained using only one specimen. From these peak stresses, Mohr diagrams can be plotted, and the shear parameters calculated. Pressure-stepping experiments inherently include errors related to micro-structural and soil state changes in between the pressure steps, and also there is the difficulty of the exact determination of the peak stress points before proceeding to the next step [28–30]. Some of these errors due to severe micro-structural changes occurring at high strains of the soil can be avoided by a tentative early stopping of the specimen deformation in the pressure-stepping experiments [29]. Furthermore, as shown by the results presented by Hashimoto et al. [30], the variations between the results of traditional or single stage triaxial tests and the pressure-stepping experiments were minor; hence, considering the many advantages that pressure-stepping experiments have over traditional triaxial tests, they are recommended and suitable for use.

Each experiment consisted of three phases: saturation, consolidation, and shearing or deformation. During the saturation phase of the experiment, the samples were subjected to incremental confining or cell pressure steps $\sigma_c = \sigma_3$ between 50 and 500 kPa along with incremental pore-fluid/back-pressure steps $\sigma_b$ between 30 and 480 kPa (maintaining a constant effective stress of 20 kPa throughout), under drained and hydrostatic conditions ($\sigma_1 = \sigma_2 = \sigma_3$). During each load step of saturation, the *B*-value of each specimen was calculated using a cell pressure increase of 50 kPa and a minimum target value of 90%, to check whether or not full saturation and the removal of entrapped pore-air conditions were attained in the specimen. After the desired *B*-value of the specimen was achieved, the second phase of the experiment or the consolidation phase was started. In the consolidation phase, the samples were consolidated under drained and hydrostatic conditions with a constant back-pressure $\sigma_b$ of 30 kPa and target cell pressures $\sigma_c = \sigma_3$ of 100/200/300 kPa, which correspond to effective confining pressures $\sigma'_c = \sigma'_3$ of 70/170/270 kPa, for the three loading/shearing stages, respectively. Each consolidation phase was performed prior to the application of vertical load or shearing of the specimen corresponding to the stage.

For the third or shearing phase, the confining and back-pressures of each consolidation stage were maintained, and the specimen was sheared anisotropically ($\sigma_1 > \sigma_2 = \sigma_3$) at fully drained conditions with a very slow constant deformation rate of 0.014 mm/min (in accordance to DIN 18137 [31]) to ensure that excess pore-water pressures were not developed during the deformation process. The shearing process for each pressure stage was generally run until peak stress (but stopped prior to reaching failure). However, for some of the tests, a continuous increase in strength without reaching a peak condition was observed. These tests were stopped after a considerable strain was achieved in order to allow additional pressure steps at higher confining pressures to be applied, without fattening the specimen and imposing excessive or severe micro-structural changes. At the end of each shearing phase, the $\sigma_1$ loading piston was retracted back (unloaded) to isotropic location before the start of the consolidation phase for the next loading step. The test data such as time duration, force (load), displacement (strain), cell, back and pore-water pressures, temperature, and volume change of specimen were recorded at logging intervals of 10 s.

The average and differential effective stresses were calculated as $p' = 1/3(\sigma'_1 + \sigma'_2 + \sigma'_3) = 1/3(\sigma'_1 + 2\sigma'_3)$ and $q = \sigma'_1 - \sigma'_3$, respectively, where $\sigma'_1$, $\sigma'_2$ and $\sigma'_3$ are the principal effective compressive stresses, which are in turn obtained by subtracting the value of the pore-water pressure $u$ in the specimen from the total principal compressive stresses $\sigma$. The peak effective friction angle $\phi'$ of the specimen is obtained using the slope $M$ of the $p'$–$q$ diagram at failure as $\phi' = \sin^{-1}\left(\frac{3M}{6+M}\right)$.

## 3. Results and Discussion

In this section, the experimental results of the CD triaxial tests on the two glacial tills are presented.

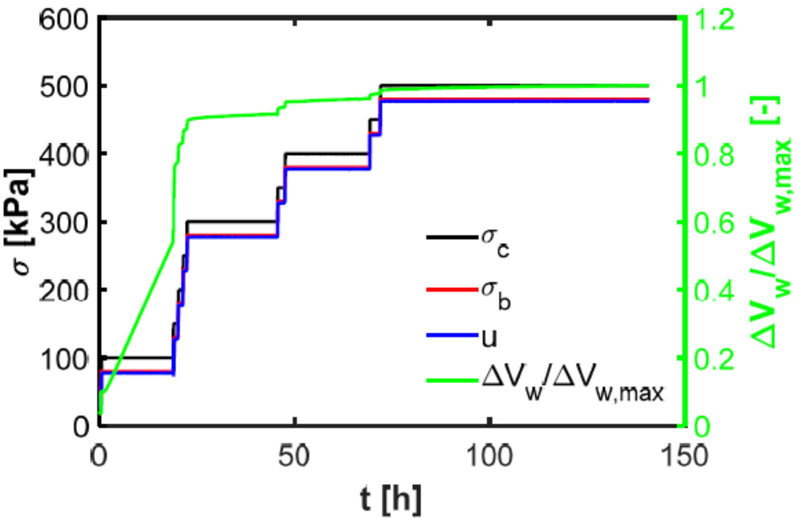
### *3.1. Saturation Phase Plots*

Figure 7 shows the time plot results for the saturation stages of the till soils at room temperature. The saturation process of each specimen was completed in around 140 h, during which time the confining pressure $\sigma_c = \sigma_3$ of the specimen was increased from around 50 to 500 kPa, maintaining an effective stress of 20 kPa in the specimen throughout. During the application of cell pressures of 50 and 100 kPa, back-pressure was applied only from the bottom of the specimen, while allowing the entrapped pore-air in the specimen to be driven out from the top of the specimen (free drainage) from time to time. Once the volumes of water entering and leaving the specimen were almost equal, indicating the near-complete removal of free pore-air in the specimen, the free drainage pipe from the top of the specimen was closed and connected to the back-pressure system, thus allowing the back-pressure to be applied from both the top and bottom faces of the specimen.

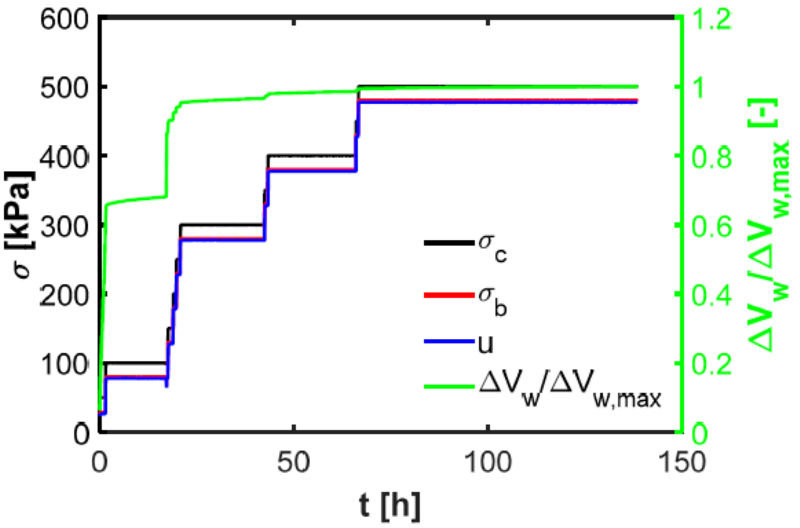
Afterwards, the confining and back-pressures were simultaneously and incrementally increased up to their maximum values, allowing the irremovable or bound pore-air or gases left in the pores to dissolve in the pore-fluid solution under high pressure conditions. After the application of a confining pressure of 500 kPa, the changes in volume of water entering the specimen $\Delta V_w$ for both till types was insignificant, and hence further increases in confining pressures were not necessary. This process enabled the target $B$-value of the specimen to be achieved, indicating the complete saturation of the samples. Comparatively speaking, observing the plots of the normalized $\Delta V_w$, as expected, the oM specimen, with its relatively finer texture, exhibited a higher resistance to the inflow of water into the specimen when compared to the mM specimen (Figure 7).

### *3.2. Consolidation Phase Plots*

In Figures 8 and 9, results of the room temperature first stage (effective confining stress $\sigma'_c = \sigma'_3$ of 70 kPa) consolidation of the triaxial tests on the two till soils are presented. The first stage consolidation was achieved by simultaneously lowering the confining and back-pressures reached during the saturation phase, i.e., the cell pressure from 500 to 100 kPa and the back-pressure from 480 to 30 kPa, thereby increasing the effective confining pressure from 20 kPa to around 70 kPa. This allowed for the expulsion of pore-water from the saturated specimens, as shown by (or equivalent to) the negative volume change $\Delta V$ of the samples seen in Figures 8 and 9. Both till soils exhibited a relatively fast consolidation process, requiring a consolidation time of around 1000 min, owing to their comparatively lower fine-grain fraction when compared to traditional fine-grained soils.

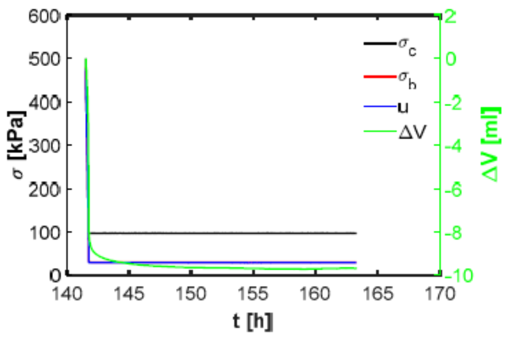



(**a**)




(**b**)

**Figure 7.** Room temperature saturation phase time plots of: (**a**) oM; (**b**) mM.

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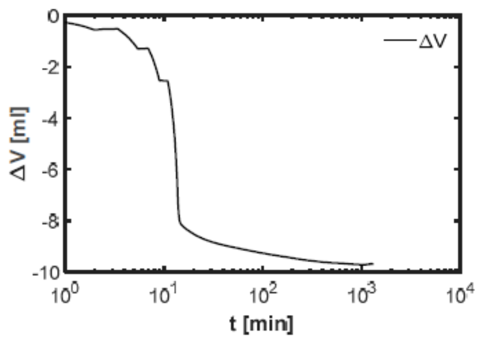


(**b**)

**Figure 8.** Consolidation phase time plots for soil oM: (**a**) pressures and volume change vs. time; (**b**) volume change vs. time.

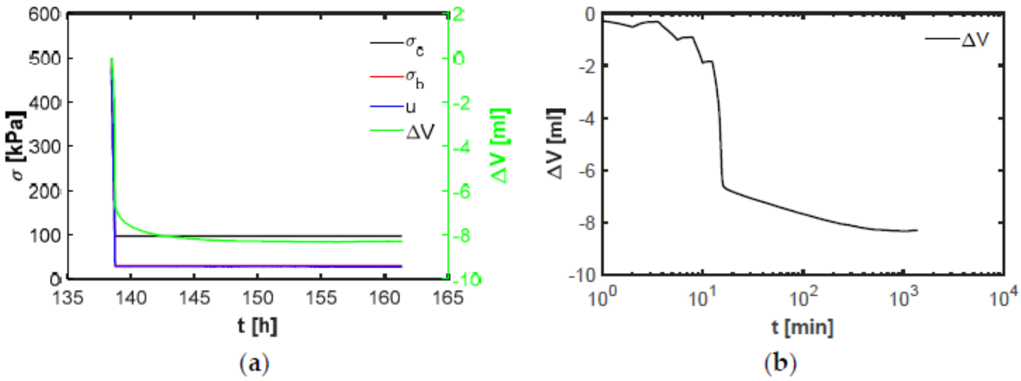


**Figure 9.** Consolidation phase time plots for soil mM: (**a**) pressures and volume change vs. time; (**b**) volume change vs. time.

### *3.3. Shearing or Loading Phase Results*

Figures 10–12 show axial strain $\varepsilon_a$ vs. differential (deviatoric) stress $q$, $p'$–$q$, and axial strain $\varepsilon_a$ vs. volumetric strain $\varepsilon_v$ plots of the shearing phase triaxial tests on the two till soils at temperatures $T$ of 20, 40 and 60 °C. Comparing the deviatoric stress and volumetric strain against shear strain results, both till soils exhibited a strain-hardening behavior until reaching near-peak conditions at all the considered temperatures, while also showing small initial contractions at the start of the tests, and then dilating (expanding) at a considerably larger magnitude towards higher shear strains (or near peak deviatoric stress conditions). The vertical drops in between the three shearing phases of the volumetric strain vs. shear strain plots of Figures 10–12 are indicators of sample shrinkage during the applications of the effective consolidation stresses (phases) of the different loading stages of the pressure-stepping experiments.

The observed dilatant behavior of the till soils during shearing is as expected, considering the high initial density of the soils (compacted to represent the actual field conditions), which is also representative of most till deposits due to high over-burden stresses of past glaciations. These findings are in agreement with previous research, which reported that dense or overconsolidated soils generally show a minor initial contraction, before dilating strongly, whereas loose or normally consolidated soils tend to primarily compress upon shearing under consolidated drained conditions [32].

When comparing the stress–strain plots for the two soils, especially for the first stage of loading ($\sigma'_c = \sigma'_3$ of 70 kPa), where the soils (or more specifically, the quartz and calcite dominated grain skeletons) are micro-structurally unaltered, oM generally exhibited a higher bulk compressive axial strain $\varepsilon_a$ at peak differential stress conditions $q$ (around 5% for oM to around 1.5% for mM), indicating a higher ductility or a lower stiffness modulus when compared to that of mM.

Analyzing the effective shear strength parameters and peak differential stresses of the soils at varying temperature conditions (Figures 10–12), overall, both soils showed a minor reduction in their effective shear strength parameters, and hence their peak differential stresses with an increase in soil temperature (a reduction in the slopes $M$ of the $p'$–$q$ diagrams at failure from 1.3560 to 1.3242 for soil oM, and from 1.4402 to 1.4026 for soil mM, and a corresponding reduction in the effective internal friction angle $\phi'$ from 33.57 to 32.85° for soil oM and from 35.50 to 34.64° for soil mM, due to heating of the soils from 20 to 60 °C; see Tables 2 and 3).

**Table 2.** Variations of the measured values of slope $M$ of the $p'$–$q$ diagrams at failure.

| Temperature (°C) | oM | mM |
|---|---|---|
| 20 | 1.3560 | 1.4402 |
| 40 | 1.3544 | 1.4258 |
| 60 | 1.3242 | 1.4026 |

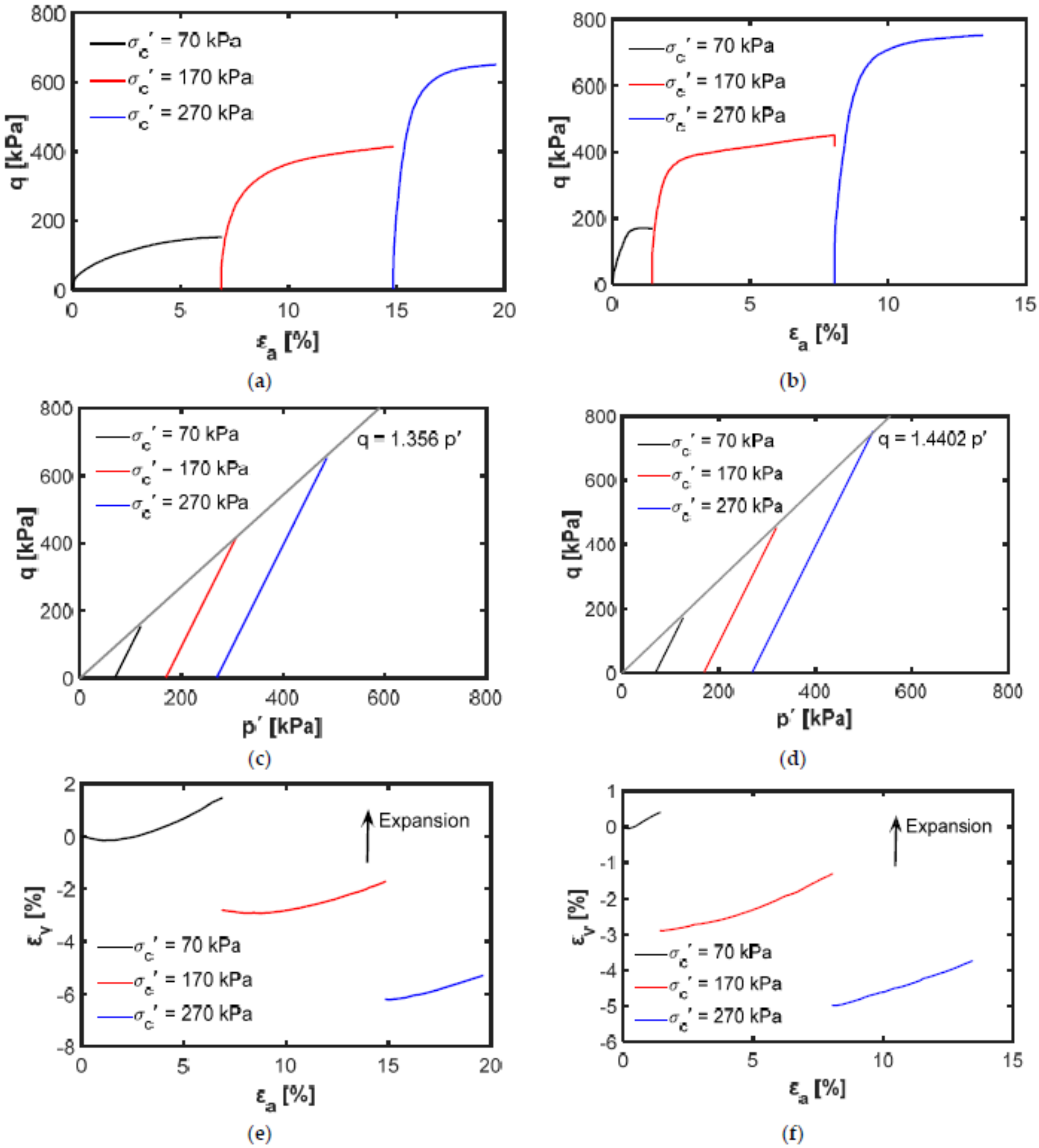


**Figure 10.** Shearing phase plots at $T$ = 20 °C of: (**a**,**c**,**e**) oM; (**b**,**d**,**f**) mM.

**Table 3.** Variations of the measured values of effective internal friction angle $\phi'$.

| Temperature (°C) | oM | mM |
|---|---|---|
| 20 | 33.57° | 35.50° |
| 40 | 33.54° | 35.17° |
| 60 | 32.85° | 34.64° |

These results are in agreement with previous findings, where dense and overconsolidated soils show a thermal dilatant (expansive) behavior after heating at elevated temperatures [7,19–21], which can in turn cause a reduction in their shear strength capacity.

However, loose and normally consolidated soils show a thermal contractive (compaction) behavior after heating, and these grain rearrangements which enable the formation of a more compact medium can then cause an increase in their effective shear strength capacity. The effects of an increase in the temperature of soils on the changes of the volumes of the grains and particle rearrangement have been discussed in more detail in Burghignoli et al. [7]. Burghignoli et al. also noted that cooling after heating does not produce significant changes in porosity or soil volume.

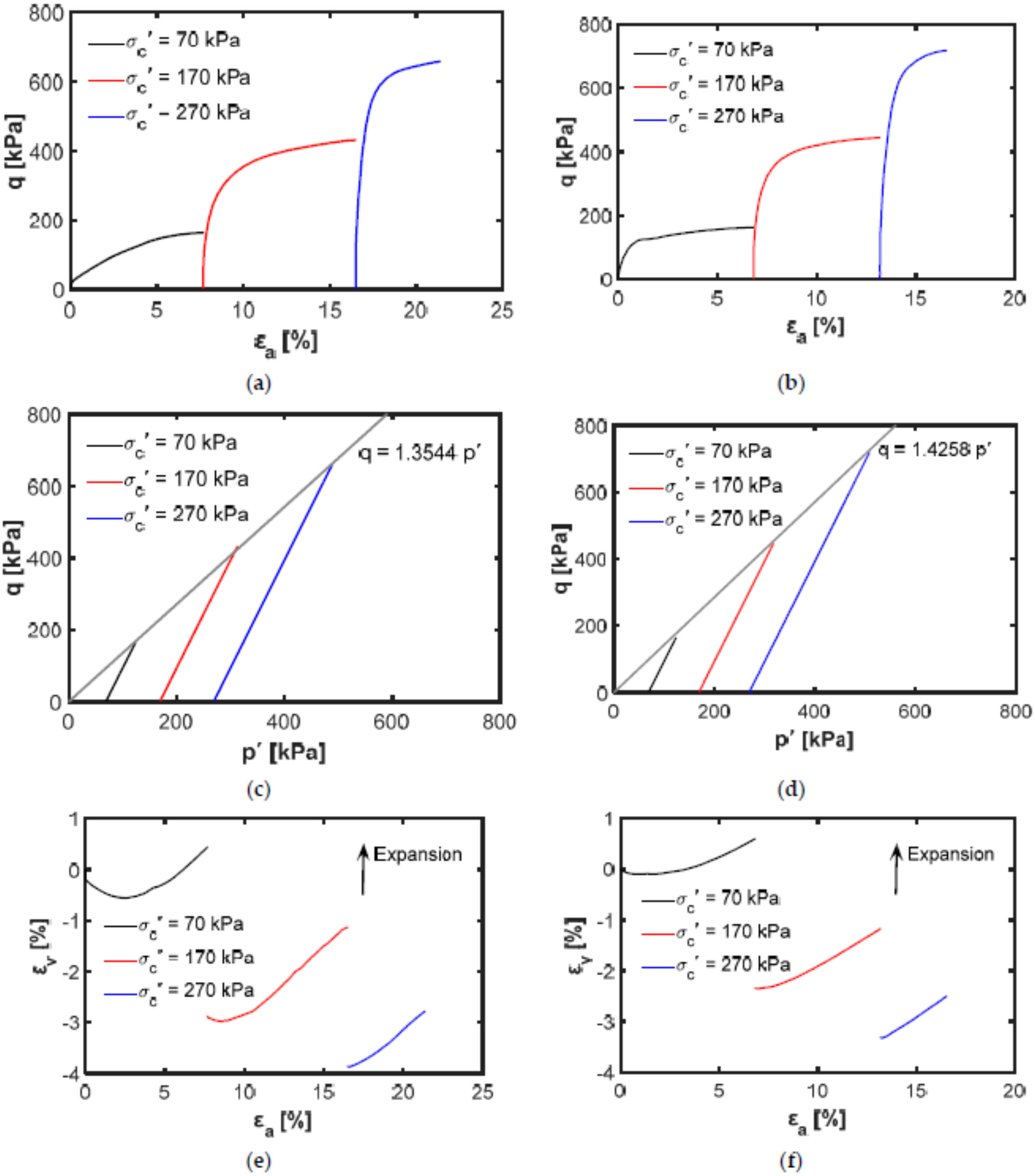


**Figure 11.** Shearing phase plots at $T$ = 40 °C of: (**a**,**c**,**e**) oM; (**b**,**d**,**f**) mM.

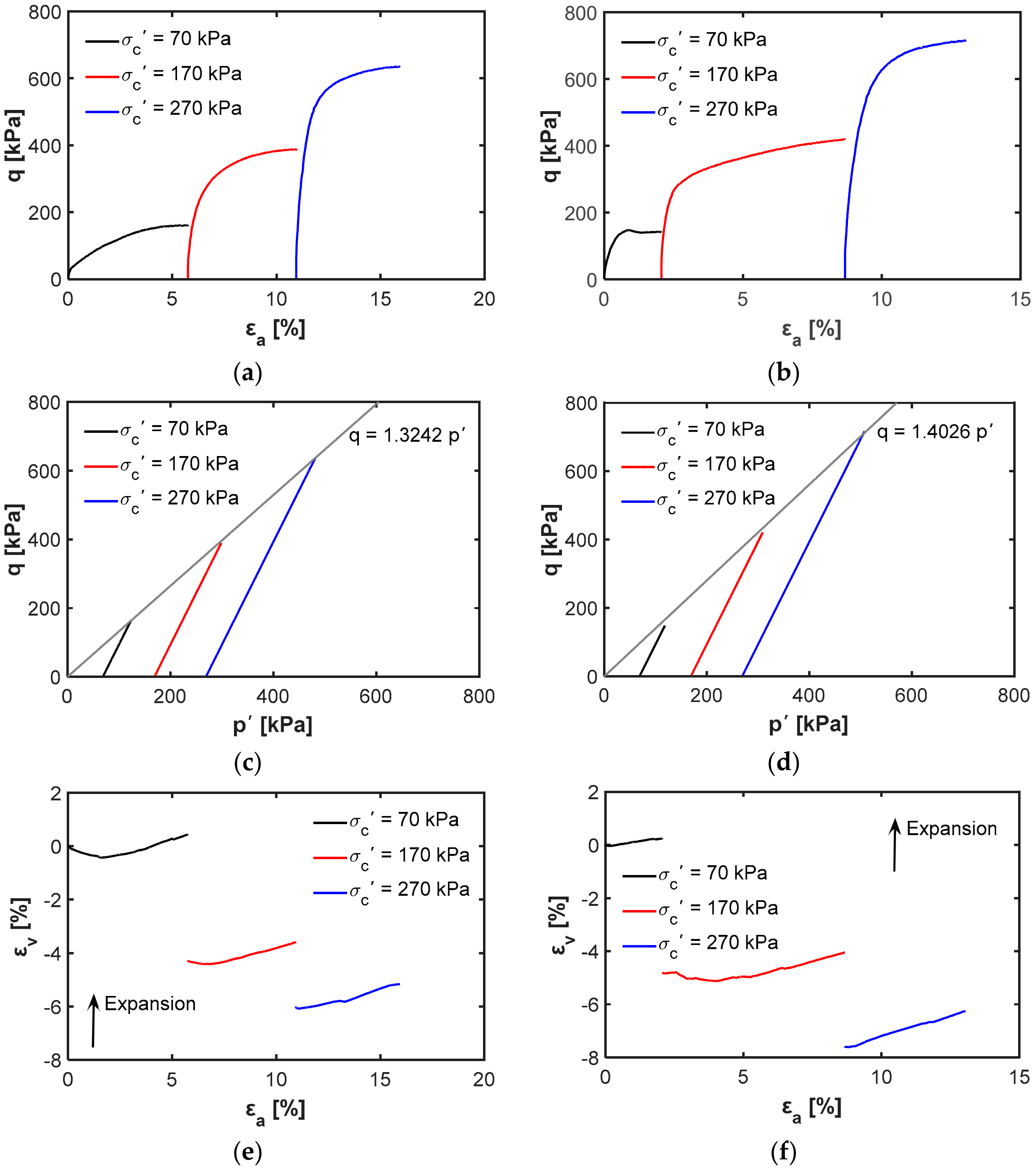


**Figure 12.** Shearing phase plots at T = 60 °C of: (**a**,**c**,**e**) oM; (**b**,**d**,**f**) mM.

Hence, the effect of temperature on the shear strength behavior of the till soils studied in this paper can be considered minimal for the temperature ranges considered in this study, because both soils showed a mild reduction in their effective friction angle or shear strength with an increase in medium temperature, with an average reduction of <1° measured for both soils, when the temperature was increased by around 40 °C above room temperature. The values of the slopes $M$ of the $p'$–$q$ diagrams at failure and the effective internal friction angles $\phi'$ of the two till soils at varying medium temperatures $T$ are shown in Figure 13, and Tables 2 and 3.

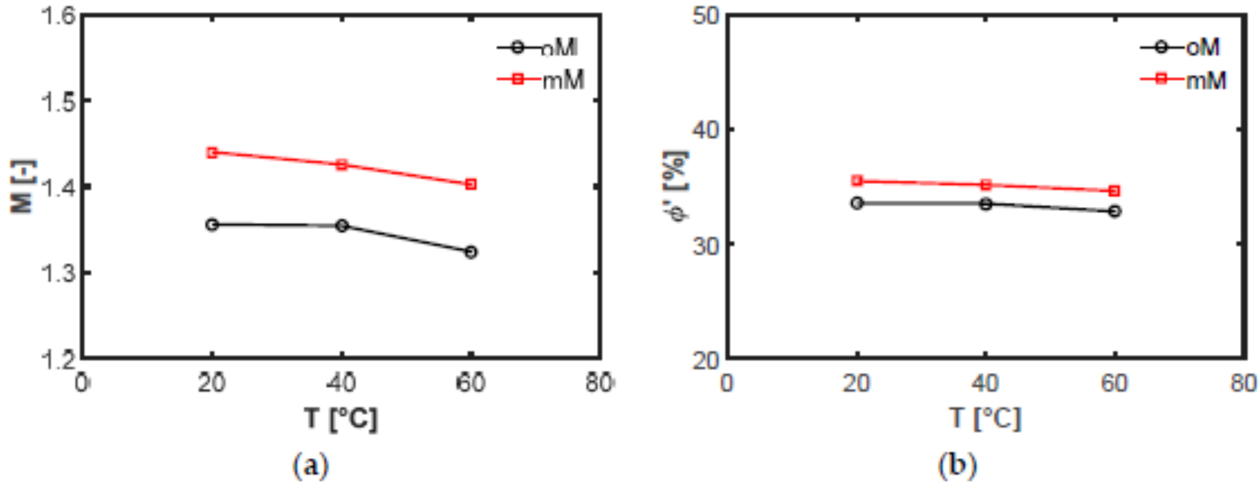


**Figure 13.** Temperature variations of: (**a**) slopes $M$ of the $p'$–$q$ diagrams at failure; (**b**) effective internal friction angles $\phi'$, of the two till soils.

Overall, the shear strength values (in terms of the obtained peak effective internal friction angles $\phi'$) of the till soils at room temperature (around 33–36°) (Figure 13b, Table 3) lay in between those of the commonly obtained values of normally consolidated clayey and silty soils (<32°) and non-uniform gravelly and dense sandy soils (>36°) from the literature [32,33], corroborating the idea that the soil depositional and mechanical models of till soils do not conform the traditional categories of coarse- or fine-grained soils [2,5], but rather fall somewhere in between. These findings are as expected, because the till soils primarily comprised or were a mixture of coarse- and fine-grained grains in their skeleton, both contributing to their overall mechanical behavior.

Moreover, till mM showed higher effective shear strength when compared to that of till oM (e.g., slope $M$ at peak failure condition of 1.4402 or effective internal friction angle $\phi'$ of 35.50° of mM compared to slope of 1.3560 and angle of 33.57° of oM at $T$ = 20 °C, see Tables 2 and 3), primarily due to its coarser texture, higher natural density, and lower plasticity (Table 1).

The findings presented in this study are mainly descriptive of the shear strength behavior and their variations with temperature of the two till deposits from the area of Heiligenhafen, northern Germany. The sample densities considered in this study are at very dense states, representing the field conditions. Considering the fact that initial density has an important influence on the effects of temperature on the effective shear strength of soils, as discussed earlier in this section, more data representing various densities are needed in future studies to fully understand the shearing characteristics of till deposits.

The outcomes of this study can contribute to the future work and analysis of the complete yielding behavior, and the development of prediction models for the estimation of the limits of elasticity or the yield locus for different densities and temperatures of till deposits. In view of these points, future tests can be conducted by analyzing the spatial variations of the till deposits by collecting more samples, and performing effective shear strength tests at varying density, temperature, and matric suction conditions.

## 4. Conclusions

The findings of a laboratory study of the shear strength behavior and the influence of temperature on the mechanical properties of two glacial till soils have been presented. The consolidated drained (CD) tests were performed on reconstituted samples using a triaxial cell capable of controlling the temperature of the specimens. The range of temperature investigated in the study was between 20 and 60 °C.

Overall, the measured effective shear strength, in terms of the obtained peak effective internal friction angles, of the till soils at room temperature ranged from 33° to 36°. These values indicated that the peak effective internal friction angles of the till soils (which generally consist of coarse- and fine-grained particles in their skeleton) lay between those of the commonly obtained values of normally consolidated clayey and silty soils (<32°) and non-uniform gravelly and dense sandy soils (>36°) from the literature, corroborating the idea that the soil depositional and mechanical models of till soils do not conform the traditional categories of coarse- or fine-grained soils, but rather fall somewhere in between.

Upon drained shearing, both soils exhibited a strain-hardening behavior until reaching near-peak conditions at all the studied temperature conditions, while also showing small initial contractions at the start of the tests, and then dilating at a considerably larger magnitude towards higher shear strain levels. The observed dilatant behavior of the till soils during shearing was as expected, considering the high initial density of the soils (compacted to represent the actual field conditions), which is also representative of most till deposits due to high over-burden stresses from past glaciations. These findings are in agreement with previous studies, which indicated that dense or overconsolidated soils generally show a minor initial contraction before then dilating strongly, whereas loose or normally consolidated soils tend to primarily compress upon shearing under consolidated drained conditions.

Overall, both soils showed a minor reduction in their effective shear strength parameters, and hence their peak differential stresses with an increase in soil temperature (a reduction in the effective internal friction angle $\phi'$ of both soils by <1° due to heating from 20 to 60 °C). These reductions in the effective shear strength parameters are in agreement with previous findings, where dense and overconsolidated soils show a thermal dilatant behavior after heating at elevated temperatures, thereby losing shear strength; in contrast, loose and normally consolidated soils showed a thermal contractive behavior after heating, thereby gaining shear strength.

The outcomes of this study provide valuable insight and data for future work and analysis of the complete yielding behavior, and the development of prediction models, for the estimation of the limits of elasticity or the yield locus for different densities, temperatures, and matric suctions of till deposits.

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