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1 **INFLUENCE OF EFFECTIVE STRESS AND TEMPERATURE**
2 **ON THE CREEP BEHAVIOR OF A SATURATED**
3 **COMPACTED CLAYEY SOIL**

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21 **Abstract**

22 The compacted clay barrier of shallow depth repositories for wastes would be
23 subjected to temperature variations. Consequently, the hydro-mechanical
24 properties of compacted clays could be progressively modified, and thus affect the
25 performance of repositories. The influence of effective stress and temperature on
26 the creep behavior of a saturated compacted clayey soil was experimentally
27 investigated by performing a series of incremental loading creep tests using a
28 temperature-controlled oedometer. Applied effective vertical stress varied from 10
29 to 1300 kPa within a large temperature range of 5°C to 70°C. The results showed
30 that the compression and swelling indices appear not to be affected by temperature,
31 whereas the yield stress decreases as the temperature increases. The secondary
32 compression is time-dependent; creep strains decrease with time till reaching a
33 stable value corresponding to a period of 10 days. The creep coefficient C_{ae}
34 increases with the increase of the effective stress and temperature. Moreover,
35 relationships between the creep coefficient C_{ae} , incremental compression index
36 C^*_c , effective stress and temperature were further analyzed. A linear relationship
37 between C_{ae} and C^*_c was observed in the considered stress range and the (C_{ae}/C^*_c)
38 ratio appears to be temperature dependent. Finally, the main results were discussed
39 and interpreted in the light of a suitable constitutive framework.

40 Keywords: compacted clay; oedometer; creep tests; effective stress; temperature.

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45 Nomenclature

C	compression index
C_c^*	incremental compression index
C_s	swelling index
C_{s_L}	swelling index (loading slope before yield stress)
C_{s_UNL}	swelling index (unloading slope)
$C_{\alpha e}$	creep coefficient
CRS	constant rate of strain test
e	void ratio
e_0	initial void ratio
EOP	end of primary consolidation
IL_{EOP}	incremental loading till t_{EOP}
$ILCr$	creep incremental loading for 10 days
I_p	plasticity index
NCL	normal consolidation line
p_0^*	yield stress for saturated conditions
t	time
t_{EOP}	time equal to the end of primary consolidation
T	temperature
UNL_{EOP}	unloading till t_{EOP}
w_N	natural water content
w_L	liquid limit
w_P	plastic limit

α constant

ε_v vertical strain ($\Delta H / H_0$)

$\dot{\varepsilon}_v$ strain rate

κ swelling index corresponding to $C_s / \ln 10$

λ compression index corresponding to $C_c / \ln 10$

σ'_p yield stress

σ'_v effective vertical stress

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63 **1. Introduction**

64 Compacted clays will be potentially used as engineering barriers for the disposal of waste
65 at shallow depths due to their low permeability, high exchange capacity and retention
66 properties¹. These repositories will be submitted to cyclic changes of temperature due to
67 climate variations over their service life (>10 000 years). These variations could affect
68 the evolution of the hydro-mechanical properties, in particular the compressibility and the
69 creep of these materials and consequently alter the long term performance of the
70 repository. This study will be focused on the impact of temperature on the long-term
71 behavior of compacted clays, and more specifically the impact of temperature variations
72 on creep.

73 When a saturated clay soil is loaded one-dimensionally, its deformation occurs in two
74 successive phases: (1) primary consolidation related to the dissipation of excess water
75 pressure; and (2) secondary compression or creep, i.e., time-dependent deformation under
76 constant effective stress. Two Hypotheses have been proposed by Ladd et al.². Hypothesis
77 A assumes that creep occurs only after the end of primary consolidation (EOP) and that
78 the strain at EOP is the same in both in-situ (thick sample) and laboratory (thin sample)
79 tests. In contrast, Hypothesis B assumes that creep occurs in the whole compression
80 process and starts simultaneously with the primary consolidation, and that the strain at
81 EOP depends on the sample thickness. To date, many models have been proposed to study
82 creep behavior of soft soils (e.g., Šuklje³; Bjerrum⁴; Mesri and Goldewski⁵; Leroueil et
83 al.⁶; Yin and Graham⁷; Grimstad et al.⁸). Detailed review of most constitutive models
84 describing the creep behavior of soft clays has been done recently by Karim and
85 Gnanendran⁹. In this context, Börgesson and Hernelind¹⁰ investigated the canister
86 settlement by modelling the shear creep effects in nuclear waste repositories using a

87 model based on Singh and Mitchell's¹¹ deviatoric creep formulation.

88 The creep coefficient C_{ae} is both time and stress dependent^{5,12-17}. Suneel et al.¹⁷ showed
89 that the creep strain increases with increasing effective stress in normally consolidated
90 state. In addition, the value of C_{ae} is related to other soil parameters (e.g. the natural water
91 content w_N , the compression index C_c and the effective stress σ'_v), but the most common
92 correlation is the C_{ae}/C_c concept developed by Mesri and co-workers^{5,18,19}. The C_{ae}/C_c is
93 considered a material constant, and is used together with the EOP e-log σ'_v curve to assess
94 the secondary compression behavior of any one soil¹⁹. Early laboratory work, in
95 particular, Walker and Raymond²⁰ highlighted a linear relationship between C_{ae} and C_c
96 on Leda clay over the entire applied stress range. This observation was confirmed by
97 many other researchers on various soils^{18,19}. Later, it was found that C_{ae} and C_c increase
98 with the effective vertical stress, reach a maximum value at a stress slightly higher than
99 the yield stress, and then decrease and finally remain constant^{14,17,21-23}. This divergence
100 about the relationship between C_{ae} and C_c could be related to the applied vertical stress
101 range values, i.e., it is more likely to observe a convex relationship at high vertical
102 stresses. Whatever is the shape of this relationship, the C_{ae}/C_c ratio was found to be
103 constant during the tests^{5,17,20,23-25}.

104 The temperature impact on the creep behavior of compacted soils has been considered in
105 a few number of studies. Based on oedometric creep tests results on Bryce clay at different
106 temperatures (from 5 to 50°C), Green¹² showed that the creep coefficient is both effective
107 stress and temperature dependent; the effect of temperature is more pronounced on C_{ae} at
108 low effective stress. Typically, under a constant effective stress of 96 kPa, C_{ae} varies by
109 37.5% when the temperature changes between 5 and 50°C¹². A series of creep tests on a
110 clayey sulphide soils within a temperature range of 5-60°C showed that creep parameter

111 was dependent on temperature, the higher the temperature, the higher the creep
112 coefficient²⁶. The creep behavior could also be evaluated by performing constant rate of
113 strain test (CRS)^{27,15}. Leroueil et. al¹⁵ suggested that the C_{ae}/C_c represents the same
114 behavior of the variation in the yield stress versus logarithmic cycle of time or strain rate,
115 i.e., $C_{ae}/C_c = \Delta \log(\sigma'_p) / \Delta \log(\dot{\epsilon}_v) = \alpha$. Boudali et al.²⁸ and Marques et al.²⁹ conducted
116 CRS tests at various temperatures to investigate the influence of temperature on the strain
117 rate-yield stress relationship of a natural clays. They found approximately parallel slopes
118 of the logarithmic strain rate-yield stress relationship at different temperatures. The key
119 concern in this study is the impact of temperature on creep for compacted clays while
120 existing studies were primarily focused on natural sensitive clays that have a specific
121 microstructure and are highly cemented.

122 As the engineered barriers are made of compacted clayey soils, a correct assessment of
123 consolidation and creep behavior of the considered material is a fundamental necessity.
124 Investigation of the creep behavior dependency on changes in stress level and temperature
125 must be done. Therefore, this paper aims to investigate experimentally the variations of
126 C_{ae} under different effective vertical stresses at various temperatures of a saturated
127 compacted clayey soils. For this purpose, a temperature-controlled oedometer was used
128 to perform tests under a wide range of stress and temperature. The saturated compacted
129 samples were submitted to incremental loading oedometer creep tests, and the creep
130 coefficient was determined for each increment load. The results were analyzed with
131 C_{ae}/C_c concept.

132 **2. Materials and methodology**

133 ***2.1 Material***

134 The study was performed on a compacted clayey soil from the East of France. The studied
135 soil is composed of 35.9% clay minerals, 46.3% quartz, 9.9% Calcite, 4.3% Feldspar, 3%
136 Plagioclase and 0.6% Gypsum. The clay minerals of the material, as determined by X-
137 ray diffractometry, are kaolinite (38.4%), illite (26.5%), interstratified illite-smectite
138 (26.2%), and chlorite (8.9%). A laser diffraction particle size analyzer (Malvern
139 Mastersizer 2000®) was used to determine the particle size distributions of the soil. The
140 soil is composed of approximately 72% of silt particles (smaller than 0.02 mm) and the
141 remaining particles (25.5%) are smaller than 80 μm . Atterberg limits (AFNOR)³⁰ for
142 studied clay were determined. The plastic limit (w_p) is 19.7%, the liquid limit (w_L) is
143 43.5% with plasticity index $I_p=23.8\%$, and the specific gravity is 2.65. The standard
144 Proctor curve showed that the maximum dry density is 1.74 Mg/m^3 at an optimum
145 moisture content of 16.5% (AFNOR)³¹. The studied material is classified as lean clay,
146 CL, according to the Unified Soil Classification System³² and A2 according to the French
147 standard for soil classification³³.

148 ***2.2 Sample preparation***

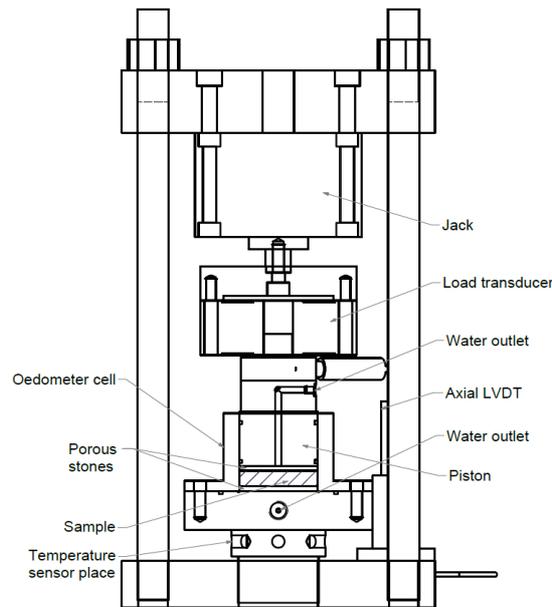
149 For the sample preparation, the dry powder ($< 400 \mu\text{m}$) was carefully mixed and wetted
150 with deaerated and demineralized to the standard optimum moisture content. The
151 prepared soils were then stored in airtight bags for at least 24 hours for moisture content
152 equilibration. Then, soil samples were statically compacted in greased stainless steel rings
153 of the oedometer cells to the maximum dry density. The samples' dimensions are 50 mm
154 in diameter and $10 \pm 0.1 \text{ mm}$ in height. The maximum compaction pressure reached is

155 1200 kPa. Initial void ratio determined in these conditions is $0,515 \pm 0.008$.

156 *2.3 Compression creep tests*

157 *2.3.1 Testing device*

158 An oedometer with temperature-control system was developed for conducting oedometer
159 creep tests, and studying the combined effects of vertical stress and temperature on soils
160 (Fig. 1). A compressed air pressure system was designed for the load application. The
161 target vertical load was applied to the sample by air pressure through pressure regulator.
162 The maximum corresponding vertical stress is 1300 kPa for 50 mm samples. Vertical
163 displacement of the sample was measured using LVDT (linear variable differential
164 transformer) sensors with an accuracy of 0.01 mm. The control of temperature was
165 obtained using a climatic chamber. It allows for working at temperatures ranged from 5
166 to 100°C with a $\pm 0.7^\circ\text{C}$ accuracy. The temperature is continuously measured and
167 recorded during the test by a temperature sensor connected to the cell, near the soil
168 sample. The system comprises also a volume/pressure controller to control the pore water
169 pressure at the base of the sample. The sample is installed between two initially dry
170 porous stones.



171

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Fig. 1. Schematic drawing of the oedometer (placed in the temperature-controlled chamber).

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2.3.2 Experimental procedures

174

The compacted sample with the confining ring was set up on the oedometer. An initial

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constant vertical stress of 10 kPa was applied to ensure the contact of loading piston with

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sample. Deaerated and demineralized water was then supplied to the sample through the

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porous element from the bottom to saturate the sample. A water pressure of 10 kPa was

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applied and maintained during the entire test at the base of the sample. The saturated

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samples were drained from the top (Fig. 1). An experimental procedure was established

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to check the material sample saturation level. Firstly, the injected water volume was

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measured as a linear function of time (over a long period of time) and secondly by

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measuring the water content of the sample at the end of the saturation phase (see Jarad³⁴).

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The saturation phase was reached in seven days. Once, the vertical swelling deformation

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of the sample at this initial vertical stress and desired temperature was stabilized, the

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incremental loading was started. The ratio of change in applied vertical stress was limited

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to 0.5 times the previous vertical stress (AFNOR)³⁵. Finally, at the end of the test, water

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content of the sample was measured and the degree of saturation was calculated and

188 confirmed to be equal to 100%, which indicates that the sample was fully saturated. In
189 the following sections, the end of the saturation phase was considered as the reference
190 initial state. It is also worth noting the concept of preconsolidation pressure considered in
191 this paper. Indeed, in its geological meaning, the preconsolidation pressure of a soil is
192 unique, constant and corresponds to its maximum overburden stress in its past stress
193 history. Otherwise, the preconsolidation pressure is assumed here as “yield stress” which
194 separates two domains: the overconsolidated domain (corresponding to low loads where
195 deformations are small and reversible) and the normally consolidated domain
196 (corresponding to high loads where deformations are more important and largely
197 irreversible). In this paper the Casagrande method is used to determine the yield stress
198 σ'_p .

199 **2.3.3 Experimental program**

200 In the context of shallow depth low activity radioactive waste disposals, the expected
201 effective vertical stresses vary between 360 and 500 kPa (corresponding to the depths
202 below 30 m), and the temperature values are supposed to be between 5 and 50°C^{36,37}. To
203 respect this context, in this study, applied effective stresses were ranged between 10 and
204 1280 kPa, and temperature was imposed between 5-70°C. The experimental program
205 consists of three test series (Table 1):

206 • Series N°1: Tests TE1a to TE4b aim to determine the compressibility parameters (C_c ,
207 C_s and σ'_p) and to evaluate the temperature effect on these parameters. The samples
208 were mechanically loaded step by step up to a given stress (From 10 to 1280 kPa),
209 then the incremental unloading tests were performed. Each loading and unloading
210 step was maintained until the end of primary consolidation (t_{EOP}) was reached. The
211 tests conducted under 5, 50 and 70°C were repeated twice to check the repeatability

212 of the results. The void ratio e and vertical stress σ'_v (e - $\log \sigma'_v$) curves at different
 213 temperatures were determined.

214 • Series N°2: Tests TE5 to TE9 aim to determine the creep coefficient C_{ae} and to
 215 investigate the effective vertical stress and temperature impact on the creep
 216 coefficient C_{ae} . The samples were incrementally loaded up to a given vertical stress
 217 (10, 16 and 30 kPa). Then, the creep incremental loading tests were performed for 10
 218 days under different effective vertical stress (from 80 to 1280 kPa). At the end of
 219 1280 kPa creep increment load, unloading increments were applied going back to 10
 220 kPa. The incremental loading and unloading steps duration was equal to the t_{EOP} .
 221 Consolidation curves (e - $\log t$) under different effective vertical stresses at various
 222 temperatures were determined. The applied temperatures are 5, 20, 50 and 70 ° C.

223 • Series N°3: Tests TE10 to TE15 performed at 20°C aim to complete the experimental
 224 data and to investigate the C_{ae} dependency on both time and effective vertical stress.
 225 The samples were incrementally loaded up to a given vertical stress (10, 16, 30 and
 226 60 kPa). Then, the creep incremental loading tests were performed for 10 days under
 227 different effective vertical stress (from 80 to 640 kPa). C_{ae} was calculated at different
 228 effective vertical stress.

229 **Table 1. List of tests in temperature-controlled oedometer cell.**

Thermomechanical tests characteristics				Compressibility parameters			Creep coefficient
Series N°	Temperature (°C)	Applied vertical stress (kPa)	Step duration	C_c (-)	C_s (-)	σ'_p (kPa)	C_{ae} (-)
1	5 - 20 - 50 - 70	10 - 1280	t_{EOP}	✓	✓	✓	-
2	5 - 20 - 50 - 70	80 - 1280	10 days	-	-	-	✓
3	20	80 - 640	10 days	-	-	-	✓

230

231 **3. Results**

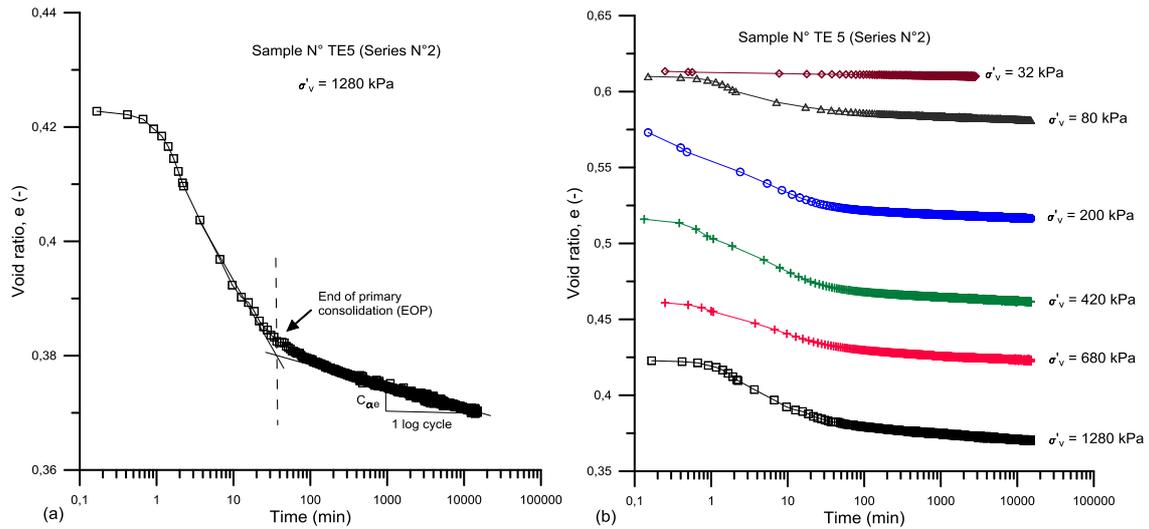
232 **3.1 Void ratio-time relationship**

233 A typical test result in terms of variation of void ratio with logarithm of time (e-log t) at
234 a single loading step in the compression tests is presented in Fig. 2a. It shows the two
235 phases of the compression process: (1) the primary consolidation, where excess pore
236 pressure dissipated; and (2) the secondary compression, that corresponds to creep, i.e.,
237 deformation under constant effective stress due to internal soil structure rearrangement.
238 The end of primary consolidation (EOP) is a point marking the transition between the two
239 phases. It is defined graphically as the point of intersection of the tangent lines when void
240 ratio is plotted against log time (Fig. 2a). In this framework, the secondary compression
241 is assumed negligible during the primary consolidation and started at the EOP. It is
242 quantified by the creep coefficient $C_{\alpha e}$ expressed by Eq. (1):

243
$$C_{\alpha e} = \frac{\Delta e}{\Delta \log(t)} \quad (1)$$

244 where Δe is the variation in void ratio and $\Delta \log t$ is the variation in time over one log
245 cycle.

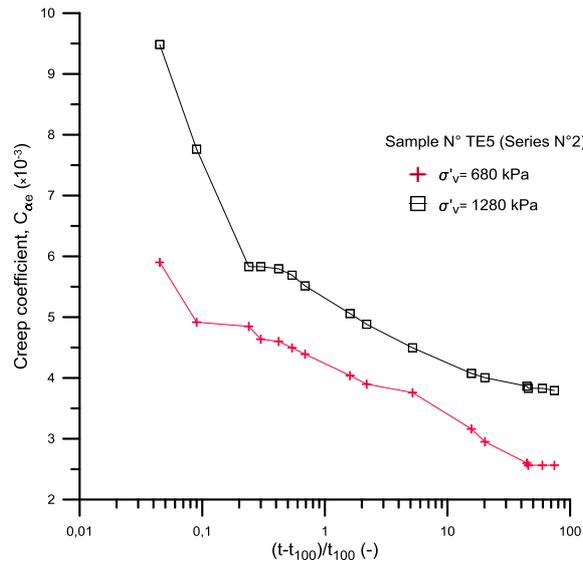
246 Fig. 2b shows the void ratio-time curves at different vertical stresses of sample TE5
247 (Temperature $T=20^{\circ}\text{C}$). As shown in Fig. 2b, the slopes of void ratio-time curves decrease
248 with time for vertical stress larger than 30 kPa, which means that $C_{\alpha e}$ of the studied
249 samples is time-dependent. It can also be observed from Fig. 2b that $C_{\alpha e}$ varies with
250 vertical stress, i.e. the creep strain increases consistently with increasing effective stress.



251

252 **Fig. 2. Void ratio-time curves at 20°C: (a) void ratio-time curve at $\sigma'_{v}=1280$ kPa; (b) void ratio-time curves at**
 253 **different effective vertical stresses.**

254 Fig. 3 shows the relationship between $C_{\alpha e}$ and the logarithm time during the secondary
 255 compression, where t_{EOP} corresponds to the time of the end of primary consolidation and
 256 consequently the start of the secondary compression. Depending on the shape of the $C_{\alpha e}$ -
 257 $\log t$ curves under a given effective stress, it can be noted that $C_{\alpha e}$ decreases considerably
 258 with time at the beginning of the creep stage then stabilizes at $(t-t_{EOP})/(t_{EOP})$ close to 100,
 259 which corresponds to 14000 min. Therefore, 10 days are enough to determine $C_{\alpha e}$.
 260 Regarding the variation of $C_{\alpha e}$ with time during the secondary compression stage, it was
 261 observed that $C_{\alpha e}$ decreases in a more marked manner at 1280 kPa compared to 680 kPa.
 262 At 1280 kPa, $C_{\alpha e}$ decreases rapidly, during the first hour, from 9.5×10^{-3} to 5.8×10^{-3}
 263 followed by an intermediate period where $C_{\alpha e}$ continues to decrease and then reaches a
 264 final value of 3.8×10^{-3} . Whereas, at 680 kPa, $C_{\alpha e}$ decreases slowly from 5.9×10^{-3} to 4.9×10^{-3}
 265 followed by an intermediate period where $C_{\alpha e}$ continues to decrease and then reached a
 266 final value of 2.6×10^{-3} . These results confirm that $C_{\alpha e}$ is both time and stress dependent.



267

268

Fig. 3. Evolution of the creep coefficient $C_{\alpha e}$ with normalized $(t-t_{EOP})/t_{EOP}$ at 20°C .

269

3.2 Void ratio-effective vertical stress behavior with temperature

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Fig. 4 shows the relationship between the void ratio e and vertical stress σ'_v ($e-\log \sigma'_v$) at

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different temperatures at t_{EOP} , including one typical $e-\log \sigma'_v$ curve at 20°C (Fig. 4a) and

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$e-\log \sigma'_v$ curves at different temperatures at $t = t_{EOP}$. Two compression tests were conducted

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under 5, 50 and 70°C following the same thermo-mechanical testing path. The two curves

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obtained under the same temperature are very similar demonstrating the good

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repeatability of the experiments (Fig. 4b and Table 2). The observed increase in void ratio

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at the initial vertical stress corresponds to the swelling deformation obtained when the

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sample is fully saturated (Fig. 4b). This increase is characterized by the swelling potential

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$\Delta H/H_0$, equivalent to $(\Delta e / (1+e_0))$. This parameter was reduced at higher temperatures

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(Fig. 4b). For example, the swelling potential decreases from 6.9% at 20°C to 1.1% at

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70°C . In the loading phase, the compressibility curves are characterized by a settlement

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which begins to appear only after the initial loading of 10 kPa during which the soil

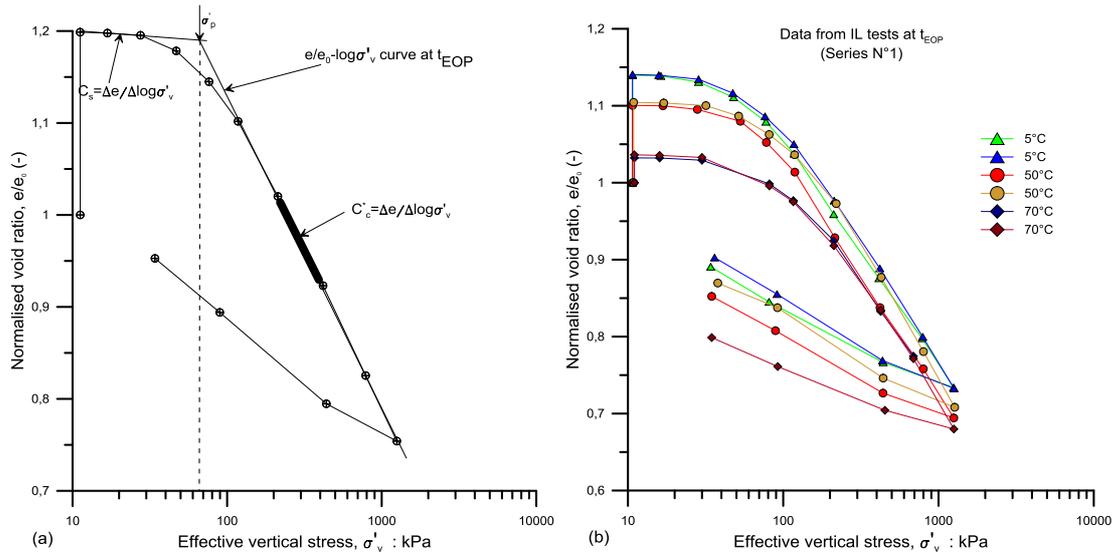
282

swells. In the unloading phase, the compressibility curves are characterized by highly

283

accentuated slopes to which correspond high values of the swelling index. This behavior

284 is related to the swelling nature of the studied clay. Similar observation was stated by
 285 many researchers³⁸⁻⁴¹. Fig. 4b also shows that, at constant temperature, the void ratio
 286 decreases with increasing vertical stress. Whereas, at constant vertical stress, the void
 287 ratio decreases with increasing temperature indicating that the soil becomes more
 288 compressible and the entire compression curve moves to the left.



289 (a) (b)
 290 **Fig. 4. Void ratio-effective vertical stress curves: (a) Void ratio-effective vertical stress curve at T=20°C at**
 291 **t_{EOP}; (b) Void ratio- stress curves at different temperatures at t_{EOP}.**

292 3.2.1 Temperature effect on the swelling and compression indices

293 Based on the $(e-\log \sigma'_v)$ curves obtained at different temperatures at t_{EOP} (Fig. 4b), the
 294 compression index $(C_c = \Delta e / \Delta \log \sigma'_v)$ and swelling index $(C_s = \Delta e / \Delta \log \sigma'_v)$ were calculated
 295 as graphically illustrated in the Fig. 4a. The values of the compression index (C_c) and the
 296 swelling index (C_s), which are defined as the slope of the normal compression line and
 297 slope of the swelling line, respectively, are given in Table 2. Fig. 5a shows the variation
 298 of the compression and swelling indices with temperature. From the obtained
 299 experimental results, summarized in Table 2, it appears that the compression and swelling
 300 indices change very slightly with temperature. On average, the compression index (C_c)

301 and the swelling index (C_s) appear be about 0.161 and 0.007, respectively.

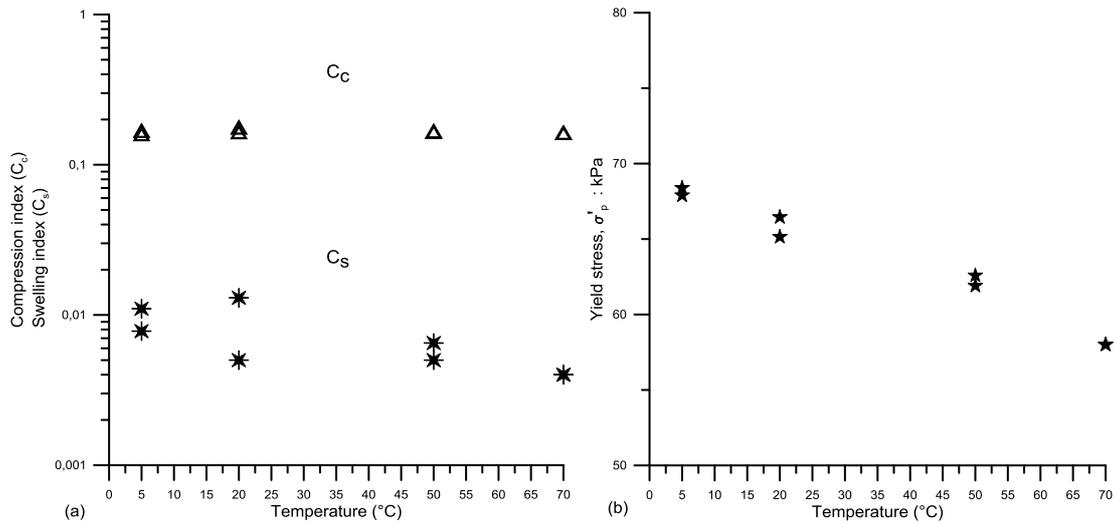
302 **3.2.2 Temperature effect on the yield stress**

303 The yield stress σ'_p of tested samples was evaluated using the Casagrande method as
304 graphically represented in Fig. 4a. The determined yield stress for tested samples at 5, 20,
305 50 and 70°C are given in Table 2. A yield stress σ'_p – temperature relationship was plotted
306 in Fig. 5b. It was found that as the soil temperature increases the yield stress σ'_p decreases.
307 For example, the percentage of the decrease in yield stress σ'_p is 14.9% due to the
308 temperature increase from 5 to 70°C. This corresponds to a negative hardening or
309 softening of the soil.

310 **Table 2. Effect of temperature on the $\Delta e/(1+e_0)$, C_c , C_{s_L} , C_{s_UNL} , and σ'_p .**

T (°C)	$\Delta e/(1+e_0)$ (%)	C_c (-)	C_{s_L} (-)	C_{s_UNL} (-)	σ'_p (kPa)
5	4.79	0.163	0.008	0.059	68.4
5	4.84	0.155	0.011	0.066	67.9
20	6.70	0.172	0.005	0.072	66.5
20	6.85	0.160	0.013	0.067	65.1
50	3.43	0.161	0.006	0.059	62.6
50	3.51	0.162	0.005	0.058	62.0
70	1.10	0.158	0.004	0.047	58.0
70	1.29	0.158	0.004	0.047	58.0

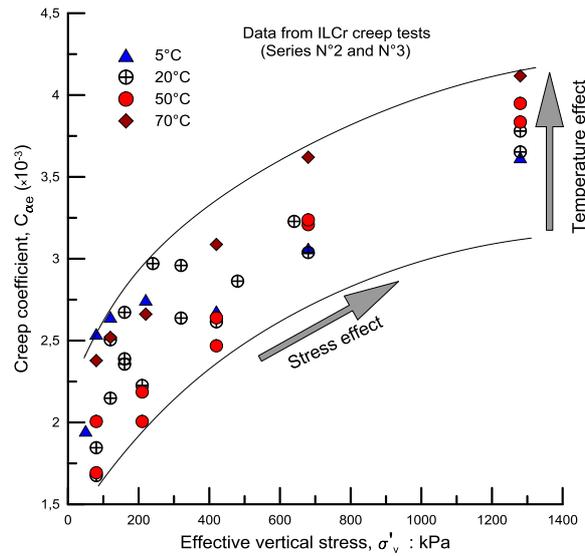
311



312
 313 **Fig. 5. Effect of temperature on the compressibility parameters: (a) the swelling index (C_s), compression index**
 314 **(C_c) and (b) the yield stress (σ'_p).**

315 ***3.3 Temperature and effective vertical stress effect on the creep coefficient***

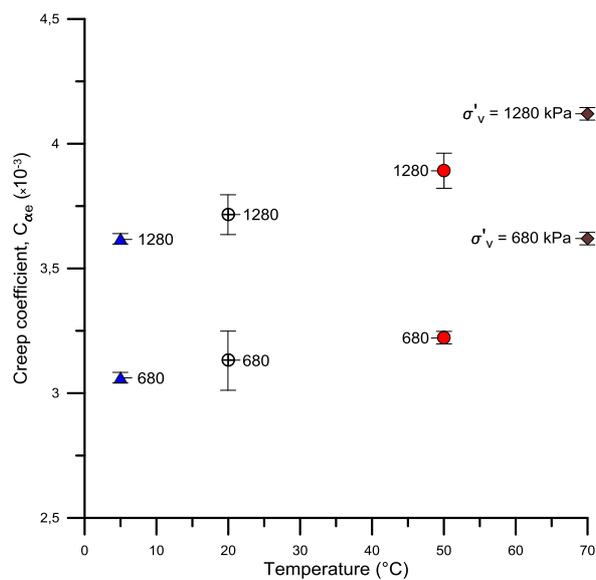
316 To investigate the combined effect of temperature and effective vertical stress on the
 317 secondary compression (creep) coefficient C_{ae} , one-dimensional ILCr oedometer creep
 318 tests were carried out on the studied material at 5, 20, 50 and 70°C (Table 1). In this study,
 319 load increments prior to the creep ones were kept until the end of primary consolidation
 320 is achieved. The duration for each creep load increment (ILCr) was more than ten days
 321 under a constant effective vertical stress (Table 1). The values of C_{ae} were determined as
 322 mentioned above in section 3.1.1 using Eq. (1). This approach was used to investigate C_{ae}
 323 for all samples. The evolution of the creep coefficient C_{ae} versus vertical stress at various
 324 temperatures is depicted in Fig. 6. Accordingly, it can be seen that C_{ae} increases with
 325 vertical stress and temperature increase, especially at higher effective vertical stress.
 326 However, a scatter was observed in the initial stages of loading, which could be related
 327 to the influence of stress level, void ratio, mechanical loading rate, loading mode and
 328 loading interval. Regardless of this, the dependency of C_{ae} on the applied effective vertical
 329 stress and temperature can be readily observed.



330

331 **Fig. 6. Secondary compression-effective vertical stress at different temperatures for all performed tests.**

332 To further investigate the effect of temperature, determined values of C_{ae} for the larger
 333 level stresses are compared. Fig. 7 shows the variation range of creep coefficient C_{ae} with
 334 temperature under higher effective stress corresponding to 680 kPa and 1280 kPa. An
 335 increase in creep coefficient with increasing temperature can be observed. For example,
 336 under the effective vertical stress of 1280 kPa, the increase percentage in C_{ae} is 13.6% as
 337 the temperature increase from 5 to 70°C. These results confirmed that the C_{ae} is dependent
 338 on the applied effective vertical stress and temperature.



339

340 **Fig. 7. Variation range of the creep coefficient with temperature at $\sigma'_v = 680$ kPa and $\sigma'_v = 1280$ kPa.**

341 **4. Discussion and analyses of results**

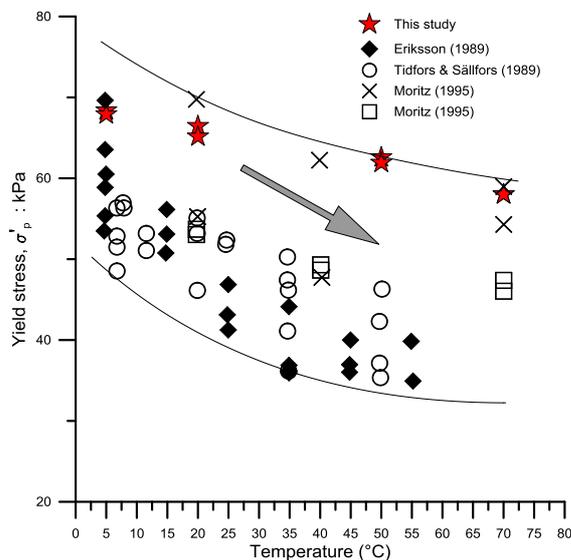
342 The effect of temperature on the soil compressibility is first discussed. Moreover, the
343 modification of the compressibility parameters with temperature is analyzed using the
344 Cam-Clay Model. The main objective of the second part of the discussion section is to
345 analyze the temperature impact on the creep coefficient in the framework of the $C_{\alpha e}/C_c$
346 concept proposed by Mesri and Goldewski⁵.

347 *4.1 Temperature effect on the soil compressibility*

348 Based on the experimental results obtained in this study, temperature has appeared to
349 modify very slightly the compression index (C_c) and swelling index (C_s). In the case of
350 remolded illitic clay, by performing isothermal oedometer tests at various temperatures,
351 Campanella and Mitchell⁴² also indicated that the variations of (C_c) and (C_s) with
352 temperature were negligible. This phenomenon has been subsequently confirmed by
353 many other authors. Furthermore, all the tests performed at various temperatures showed
354 an increase in the swelling index upon mechanical stress release when greater vertical
355 stresses were reached. This behavior is commonly associated with the swelling nature of
356 the clay³⁸⁻⁴¹. Mohajerani et al.⁴³ and Crisci et al.⁴⁴ related the observed swelling index
357 increase to the mechanical degradation of the material when subjected to high stresses
358 and to various loading and unloading cycles.

359 The effect of temperature on the yield stress, which defines the limit between elastic and
360 plastic domains, has been studied. The results obtained on compacted samples at 5, 20,
361 50 and 70°C showed a decrease of this parameter with increasing temperature. A decrease
362 of this parameter with the temperature leads to a contraction of the elastic domain. As
363 shown in Fig. 8, similar results were obtained on structured and natural soils by many

364 researchers^{26,28,29,45-47}. This phenomenon could be related to the decrease in adsorbed
 365 water of clay particles. This reduction facilitates formation of mineral to mineral contacts
 366 because water acts as an elastic material between two clay particles and consequently
 367 produces plastic deformation and reduces the elastic domain^{45,48}.



368

369 **Fig. 8. Evolution of the yield stress with temperature: Comparison of the results obtained here with**
 370 **oedometric compression tests on different clayey materials (Eriksson 1989; Tidfors and Sällfors 1989;**
 371 **Moritz 1995).**

372 Several relationships have been proposed in the literature to describe the evolution of the
 373 yield stress as a function of temperature (Laloui et Cekerevac⁴⁹; Cui et al.⁵⁰). Hueckel and
 374 Borsetto⁵¹ were the first to propose an extension of the modified Cam-Clay Model to take
 375 into account the effect of temperature in the case of saturated soils:

$$376 \quad p_0^*(T) = p_0^*(T_0) + \alpha_1 \Delta T + \alpha_2 \Delta T |\Delta T| \quad (2)$$

377 where p_0^* is the yield stress in saturated state at a reference temperature (room
 378 temperature) T_0 , T is the current temperature, $\Delta T = T - T_0$ stands for the temperature
 379 difference with respect to a reference temperature and α_1 and α_2 are the coefficients
 380 depending on thermal sensibility of the soil. By fitting experimental data, p_0^* , α_1 and α_2
 381 were determined (Table 3). Afterwards, the compressibility behavior with temperature
 382 can be well simulated in the framework of the Cam-Clay Model using the equation (2)

383 and the calibrated parameters given in Table 3. In this model, the compression index (C_c)
 384 and the swelling index (C_s) are related to $\lambda(0)$ ($\lambda=C_c/\ln 10$) and κ ($\kappa = C_s / \ln 10$),
 385 respectively. These Cam Clay parameters are for volumetric strain in isotropic stress.

386 **Table 3. Calibrated constitutive parameters.**

C_c (-)	$\lambda(0)$ (-)	C_s (-)	κ (-)	p^*_0 (kPa)	α_1 (-)	α_2 (-)
0.161	0.070	0.007	0.003	66.28	-0.0909	-0.0008

387 **4.2 Temperature effect on the creep coefficient**

388 A logarithmic function was used to fit oedometer tests data of void ratio against time after
 389 the primary consolidation (Fig. 2a). The results obtained on compacted samples at 5, 20,
 390 50 and 70°C indicated an increase of C_{ae} at higher temperatures. For instance, under the
 391 effective vertical stress of 1280 kPa, the increase percentage in C_{ae} is 13.6% as the
 392 temperature increase from 5 to 70°C. These results revealed that the creep behavior of the
 393 tested compacted clayey soils is both stress and temperature dependent. The increase in
 394 creep coefficient at higher temperature could be explained by the reduction in viscosity
 395 of soil skeleton and pore water⁵².

396 The Mesri and Goldewski⁵ concept was adopted here to analyze the long term behavior
 397 of the studied clayey soil with temperature. For example, the value of C_{ae} at 1280 kPa,
 398 higher effective vertical stress, was chosen for each temperature-controlled oedometer
 399 creep test. The relationship between the maximum C_{ae} and C_c , defined as the slope of the
 400 NCL, for each of the three temperatures shows that the ratio C_{ae}/C_c varies in a narrow
 401 range from 0.022 to 0.026. Table 4 summarizes the values of the C_{ae}/C_c ratio at different
 402 temperatures. All the values of C_{ae}/C_c lie within the range of 0.025–0.075 proposed by
 403 Mesri and Godlewski⁵ for a number of inorganic clays and silts. The results show also
 404 that the C_{ae}/C_c ratio increases with increasing temperature. As the compression index C_c
 405 changes slightly with temperature, the increase in the C_{ae}/C_c is due essentially to the

406 increase of the creep coefficient C_{ae} with increasing temperature. Then, it can be
 407 concluded that the C_{ae}/C_c ratio of the compacted soil is temperature dependent.

408 **Table 4. Influence of temperature on the C_c , C_{ae} and the C_{ae}/C_c ratio at $\sigma'_v = 1280$ kPa.**

T (°C)	C_c (-)	$C_{ae} (\times 10^{-3})$	C_{ae} (-)	C_{ae}/C_c (-)
5	0.163	3.619	0.0036	0.022
20	0.172	3.780	0.0038	0.022
50	0.161	3.949	0.0040	0.025
70	0.158	4.112	0.0041	0.026

409 By examining closely the e - $\log \sigma'_v$ curves obtained at different temperatures, it appears
 410 that these curves are not perfectly linear during loading and unloading, especially for the
 411 initial loading stages (Fig. 4). Consequently, to further explore effects of temperature and
 412 effective vertical stress on the C_{ae}/C_c ratio, an incremental compression index C_c^* was
 413 defined by Eq. (3) as the change in void ratio during the load increment for the samples
 414 of series N°1. It should be pointed out that C_c^* differs from the compression index defined
 415 as the slope of the NCL. This approach was adopted by many other researchers^{14,23,25}.

416
$$C_c^* = \frac{\Delta e}{\Delta \log \sigma'_v} \quad (3)$$

417 where C_c^* is the incremental compression index; Δe is the change in void ratio over one
 418 load increment; $\Delta \log \sigma'_v$ is the change in stress over the same load increment correspondingly.
 419 It can be seen from the Fig. 9 that, during the initial loading stages, C_c^* increased almost
 420 linearly with effective vertical stress, then it increased more slowly and finally tended to
 421 be a constant value in the final loading stages. Fig. 9 also shows that, at higher vertical
 422 stress from 400 kPa to 1280 kPa, the incremental compression index C_c^* was not
 423 depended on temperature, particularly at 20 and 50°C.

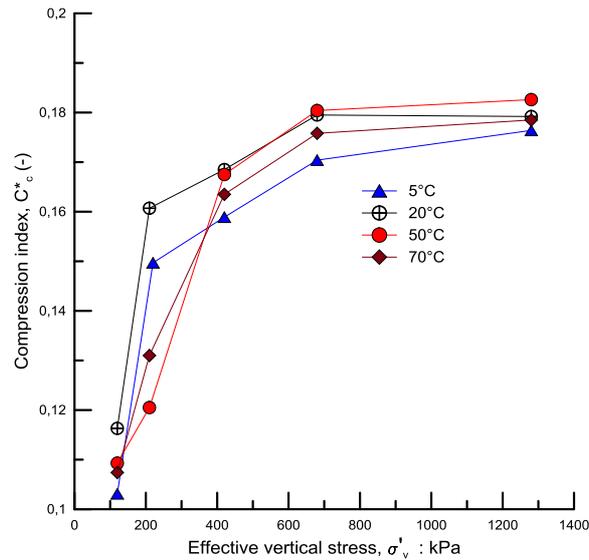


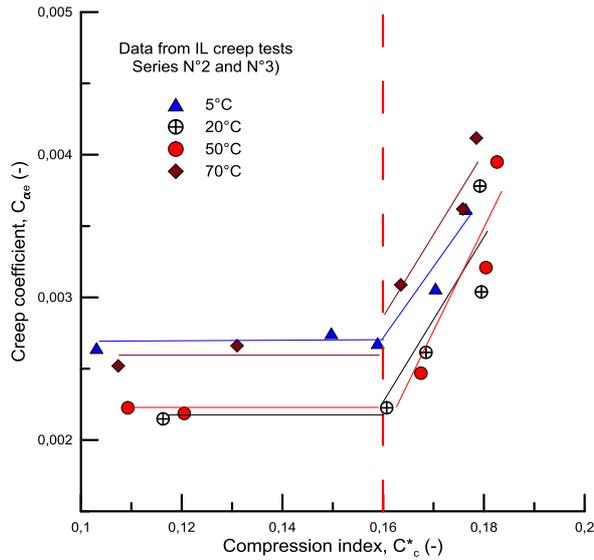
Fig. 9. Variation of C^*_c with applied vertical stress at different temperatures.

424

425

426 From the analysis mentioned above, it was shown that both the incremental compression
 427 index C^*_c and the secondary compression index C_{ae} are functions of effective vertical
 428 stress. The relationship between C_{ae} and C^*_c at different temperatures was investigated
 429 (Fig. 10). This evolution shows a limit value of C^*_c equal to 0.16, corresponding to an
 430 effective vertical stress of 420 kPa. The evolution of C_{ae} with C^*_c is quite constant at C^*_c
 431 values lower than 0.16 while C_{ae} increases in a more marked manner with C^*_c values
 432 higher than 0.16. Regarding the C^*_c values above the limit value, C_{ae} increases linearly
 433 with C^*_c (Fig. 10). The slopes of this linear increase of C_{ae} with C^*_c at 5, 20, 50 and 70°C
 434 are 0.0186, 0.0179, 0.0182 and 0.0209, respectively. It was found that the C_{ae}/C^*_c ratio
 435 increases with temperature increase (Fig. 11). Fig. 11 shows also the evolution of C_{ae}/C_c
 436 ratio with temperature.

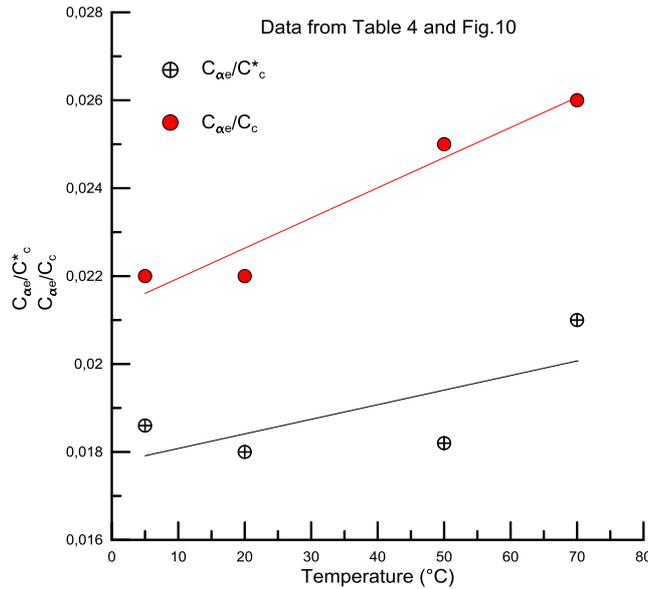
437 Based on the obtained results, it can be concluded that the concept of (C_{ae}/C^*_c) ratio may
 438 also be applied to the used material in this study in the range of C^*_c higher than 0.16. On
 439 conclusion, in the light of these findings, the ratio of C_{ae}/C^*_c could be assumed
 440 temperature dependent for the studied compacted soil.



441

442

Fig. 10. Evolution of $C_{\alpha e}$ versus C^*_c .



443

444

Fig. 11. $C_{\alpha e} / C_c$ and $C_{\alpha e} / C^*_c$ versus temperature.

445

5. Conclusions

446

The influence of effective stress and temperature on the creep behavior of a saturated

447

compacted clayey soil was experimentally investigated by performing a series of

448

temperature-controlled oedometer tests. The $e - \log \sigma'_v$ and $e - \log t$ curves were plotted to

449

determine the swelling index C_s , compression index C_c , incremental compression index

450 C_c^* , and creep coefficient C_{ae} . Moreover, different relations such as $C_{ae}-\sigma'_v$, $C_{ae}-(t-$
451 $t_{EOP})/t_{EOP}$, $C_{ae}-C_c$, and $C_{ae}-C_c^*$ were analyzed. Conclusions can be drawn as follows:

452 1. The swelling potential ($\Delta e/(1+e_0)$) is affected by temperature, it decreases as
453 temperature increases.

454 2. The compression index (C_c) and swelling index (C_s) vary slightly in the range of
455 studied temperatures.

456 3. The yield stress (σ'_p) is temperature dependent, it was found that as the soil
457 temperature increases the yield stress σ'_p decreases.

458 4. The creep coefficient C_{ae} and the incremental compression index C_c^* are both
459 stress-dependent and increase almost linearly with the effective stress increase.

460 5. The creep coefficient C_{ae} increases with increasing temperature, especially at
461 higher effective vertical stresses. Whereas, the incremental compression index C_c^*
462 could be considered independent of temperature.

463 6. The slope of the $C_{ae} - C_c^*$ depends on a limit value of C_c^* : for $C_c^* < 0.16$ a constant
464 evolution of C_{ae} with C_c^* is observed, while for $C_c^* > 0.16$ C_{ae} increases linearly
465 with C_c^* . In addition, this linear relationship appears to be dependent on
466 temperature, with a slightly higher (C_{ae}/C_c^*) ratio at higher temperatures due to
467 the increase of C_{ae} with increasing temperature.

468 Furthermore, the results of this work allowed information to be gathered for better
469 understanding the creep behavior of compacted clayey soils as a function of effective
470 vertical stress and temperature. The obtained data will be also used to model the behavior
471 of structures made up of compacted soils under the effect of thermal variations in the long
472 term.

473

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