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# **Effect of temperature on the shear strength of soils and soil/structure interface**

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24 **Abstract**

25 In the present work, shear behaviour of soils and soil/concrete interface is  
26 investigated through direct shear tests at various temperatures. Conventional direct  
27 shear apparatus, equipped with a temperature control system, was used to test sand,  
28 clay and clay/concrete interface at various temperatures (5°C, 20°C and 40°C).  
29 These values correspond to the range of temperatures observed near thermoactive  
30 geostructures. Tests were performed at normal stress values ranging from 5 kPa to  
31 80 kPa. The results show that the effect of temperature on the shear strength  
32 parameters of soils and soil/concrete interface is negligible. A softening behaviour  
33 was observed during shearing of clay/concrete interface, which was not the case with  
34 clay specimens. The peak strength of clay/concrete interface is smaller than the  
35 ultimate shear strength of clay.

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38 Keywords: shear strength; temperature; soil/structure interface; friction angle;  
39 thermoactive geostructure.

40

## 41 **1. Introduction**

42 Thermo-mechanical behaviour of soils has been a major research topic during the  
43 past two decades. The studies cover underground structures which are subjected to  
44 thermal changes including radioactive waste disposal, thermoactive geostructures, oil  
45 recovery, petroleum drilling, high-voltage cables buried in soils (Cekerevac 2003;  
46 Brandl 2006; Abuel-Naga et al. 2007; Hueckel et al. 2009; Cui et al. 2009). In these  
47 contexts, several works focus on the effect of temperature on the shear strength of  
48 soils but they are mainly limited to the temperature range of 20°C - 100°C (Hueckel &  
49 Pellegrini 1989; Hueckel & Baldi 1990; Robinet et al. 1997; Burghignoli et al. 2000;  
50 Graham et al. 2001; Cekerevac 2003; Ghahremannejad 2003). In the case of  
51 thermoactive geostructures, such as retaining walls or pile foundations, the soil  
52 temperature can vary from 5°C to 40°C (Brandl 2006; Boënnec 2009; Yavari et al.  
53 2014a). However, few works investigate the effect of temperature on the shear  
54 strength of soil for this range of temperature.

55

56 In terms of temperature effect on shear strength, conflicting results could be detected  
57 from the literature review. Hong et al. (2013) argued that the effects of temperature  
58 on shear strength of clay are strongly dependent on the volume change induced by  
59 heating. On one hand, thermal expansion leads to a decrease of soil strength; on the  
60 other hand, the thermal contraction hardens the soil and makes the shear strength  
61 increase. According to Hamidi et al. (2014), heating could make the soil friction angle  
62 decrease, increase or stay unchanged. The soil shear behaviour is found to be  
63 dependent on its mineralogy, the loading history and the applied experimental  
64 method.

65

66 While various studies focus on the thermo-mechanical behaviour of clay, few works  
67 investigate the thermal effect on sand. Thermal consolidation tests performed by  
68 Recordon (1993) on fine sand in the range of 2°C and 40°C show that the  
69 compressibility parameters (compression index, modulus and over-consolidation  
70 ratio) are independent of temperature. The same observation was made by Saix et  
71 al. (2000) on clayey silty sand between 30°C and 70°C.

72

73 Direct shear tests have been widely used to evaluate the shear behaviour of soil and  
74 soil/structure interface. After Lemos and Vaughan (2000), shear strength of  
75 sand/structure interfaces, always smaller than that of sand, mainly depends on the  
76 roughness of the interface. When this latter is similar to the grains size, the  
77 sand/structure shear strength will approach to that of sand. For clayey soils, the  
78 residual shear strength at interface is close to that of clay and it does not depend on  
79 surface roughness.

80

81 In the case of thermoactive geostructures, heat exchange between the geostructures  
82 and the surrounding soil might influence the behaviour of the soil/structure interface.  
83 Interface behaviour, which is already of complex nature, is therefore a major concern  
84 in thermoactive geostructures under the coupled thermo-mechanical loadings.  
85 However, few works consider the effect of temperature on the shear behaviour of  
86 soil/structure interface (Di Donna and Laloui 2013; Murphy and McCartney 2014; Di  
87 Donna et al. 2015).

88

89 In this study the effect of temperature on shear strength behaviour of soils and  
90 soil/structure interface is extended to the range of low temperatures (5°C – 40°C)

91 pertinent to the case of thermoactive geostructures. Direct shear box, equipped with  
92 temperature control system, was used to test sand, clay and clay/concrete interface  
93 under rather small normal stresses (5 – 80 kPa).

94

## 95 **2. Experimental techniques and materials used**

96 A direct shear apparatus, equipped with a temperature control system, was used to  
97 investigate the shear behaviour of soil and soil/concrete interface. A general view of  
98 the system is shown in Figure 1. A copper tube was accommodated in the shear box  
99 container and connected to a heating/cooling circulator. Water with controlled  
100 temperature circulates inside the copper tubes via the circulator. These tubes are  
101 immersed in water inside the shear box. This system allows controlling the  
102 temperature of the soil specimen inside the cell without altering the mechanical parts  
103 of the cell. The heating/cooling circulator, a cryostat, is able to impose a temperature  
104 in the range of -20°C to 80°C. Two thermocouples were installed in the box: one  
105 below the shear box and the other at the water surface. The container was thermally  
106 insulated using expanded polystyrene sheets. The soil (or soil/structure) was  
107 sandwiched between two porous stones and two metallic porous plates. A  
108 preliminary test was performed to verify the temperature homogeneity in the  
109 container during thermal loading paths. Two thermocouples were inserted inside the  
110 soil specimen and the temperature of the cell was changed following the same rate  
111 that was applied latter in the mechanical tests. The results show that the temperature  
112 inside the specimen is similar to that inside the container (Figure 2) confirming the  
113 temperature homogeneity of the system (the imposed temperature is that of water in  
114 the heating/cooling circulator outside the shear apparatus). For the direct shear tests,

115 the thermocouples inside the shear box were not used in order to avoid its possible  
116 influence on the specimen's mechanical behaviour.

117

118 In the present work, tests were performed on Fontainebleau sand, Kaolin clay, and  
119 Kaolin clay/concrete interface. Actually, literature review shows that the effect of  
120 temperature can be expected on the strength parameters of clay and clay/concrete  
121 interface while the behaviour of sand is independent of temperature in the range of  
122 5°C – 40°C. Testing sand at various temperature in this study is helpful to evaluate  
123 the performance of the testing device and the repeatability of the experimental  
124 procedure. The physical properties of Fontainebleau sand are: particle density  $\rho_s =$   
125 2.67 Mg/m<sup>3</sup>; maximum void ratio  $e_{max} = 0.94$ ; minimum void ratio  $e_{min} = 0.54$  (De  
126 Gennaro et al. 2008); and mean diameter  $D_{50} = 0.23$  mm. The grain size distribution  
127 of the sand used is shown in Figure 3. To perform direct shear test, dry sand was  
128 directly poured into the shear box and slightly compacted to a density of 1.50 Mg/m<sup>3</sup>.  
129 This value, corresponding to a relative density of 46%, is similar to that in the works  
130 of De Gennaro et al. (2008), Kalantidou et al. (2012), and Yavari et al. (2014b). After  
131 the compaction, distilled water was added to the container to fully saturate the sand  
132 specimen and to immerse the shear box.

133

134 The Kaolin clay has a liquid limit  $w_L = 57\%$ , a plastic limit  $w_P = 33\%$ ; and a particle  
135 density  $\rho_s = 2.60$  Mg/m<sup>3</sup> (Frikha, 2010). The grain size distribution of Kaolin clay,  
136 obtained by laser diffraction method, is shown in Figure 3. To prepare a soil sample,  
137 the clay powder was first mixed with distilled water at  $1.5w_L$  and then consolidated in  
138 an oedometer cylinder (with an internal diameter of 100 mm) under a vertical stress  
139 of 100 kPa. At the end of the consolidation phase, the soil sample (having a void ratio

140 of 1.35) was removed from the cylinder and cut into blocks of dimensions 60 x 60 x  
141 20 mm and inserted into the shear box for testing the shear behaviour of clay.

142

143 To test the clay/concrete interface the thickness of the sample was reduced to 10  
144 mm. A piece of concrete with the thickness of  $10 \pm 2$  mm was cut and solidly fixed to  
145 the lower half of the shear box. The maximum roughness detectable by the naked  
146 eye is in the order of 0.7 mm (see Figure 4). It should be noted that the same piece  
147 of concrete was used in all tests in order to maintain a similar roughness. Actually, as  
148 the test was performed only with clay (not with sand) and under low stresses, the  
149 roughness of the concrete surface was assumed to remain intact after the tests.

150

151 The loading paths applied are shown in Figure 5. For each test, after the installation  
152 of the system, a normal stress of 100 kPa was applied to the sample (path A-B); this  
153 value is equal to the pre-consolidation pressure of the clayey sample. Thus, applying  
154 such normal stress does not significantly modify the soil porosity (for both sand and  
155 clay). Note that this loading was applied by steps of 20 kPa. Load was increased  
156 once the vertical displacement stabilised. The range of stress considered in this  
157 study mainly corresponds to shallow geostructures (retaining walls, shallow  
158 foundations) or small-scale tests. Actually, most of the works on the thermo-  
159 mechanical behaviour of soils have been performed at higher stress range (which  
160 mainly corresponds to deep geostructures).

161

162 The soil temperature was then increased from the initial value ( $20^{\circ}\text{C}$ ) to  $40^{\circ}\text{C}$  by  
163 increments of  $5^{\circ}\text{C}$  (path B-C). Each increment was kept for 15 minutes. The results  
164 of this part show that vertical displacement stabilised within this period. Overall, it

165 could be stated that the soil temperature changed by 20°C in 3 h (with an average  
166 rate of 7°C/h). Once temperature reached 40°C, it was kept constant for two hours in  
167 order to permit the dissipation of excess pore water pressure induced by heating.  
168 This value of 40°C corresponds to the maximum value of temperature tested in the  
169 present work. For shearing tests at 40°C (Figure 5a), the normal stress was  
170 decreased to the desired value (path D-E) prior to shearing. For shearing tests at  
171 20°C (Figure 5b) and 5°C (Figure 5c), the soil temperature was first incrementally  
172 decreased to the desired temperature (path C-D). Each increment, of 5°C, took  
173 approximately 30 minutes. Cooling was performed at almost the same rate as  
174 heating (7°C/h). Finally, the normal stress was decreased to the desired value (path  
175 D-E) prior to shearing.

176

177 Such specific stress path has been chosen to ensure that all the shearing tests start  
178 from the thermo-elastic domain and at similar soil densities. As a result, the effect of  
179 temperature and normal stress on the shear behaviour would be better detected,  
180 without coupled effects induced by thermal consolidation. Actually, the point C in the  
181 stress path (100 kPa of normal stress and 40°C) corresponds to the maximum  
182 temperature and normal stress that the soil specimen has been subjected to prior to  
183 shearing.

184

185 For the tests on clay or clay/concrete interface, shearing rate should be small enough  
186 in order to ensure that no excess pore pressure was generated during the test and  
187 the sample was sheared under drained conditions (AFNOR, 1994; ASTM 1998). The  
188 shear rate chosen, 14 µm/min, is small enough to avoid the effect of shear rate on  
189 the soil behaviour following the work of Bhat et al. (2013).



190

191 For granular soils the shear rate could be higher because the consolidation is faster.

192 In the tests on sand the shear displacement was applied at the rate of 0.2 mm/min.

193 The maximum shear displacement at which shearing stops is set to 6 mm. This value

194 is 10% of the soil specimen size in the shear direction.

195

### 196 **3. Experimental results**

197 Results of tests on sand are shown in Figures 6-8. Under each normal stress and

198 each temperature two tests were conducted in order to check the repeatability of the

199 experiments. For the tests at 5°C, as could be seen in Figure 6a the shear stress

200 increases with horizontal displacement increase and the failure is of ductile type.

201 Figure 6b shows the vertical displacement during the shear process. The results

202 show a contracting phase followed by a dilating one under higher normal stresses. At

203 low normal stresses, the soil at the interface tends to dilate from the beginning to the

204 end of the shear process. It can be noted that the repeatability of the results on

205 vertical displacement was quantitatively less than the shear stress. Maximum shear

206 strength observed as a function of normal stress is shown in Figure 6c. The

207 maximum shear stress and the normal stress can be well correlated with a linear

208 function and a friction angle of 36° can be then determined from these results (with

209 no cohesion).

210

211 Experimental results on sand at 20°C are shown in Figure 7. As in the case of 5°C,

212 the behaviour is of ductile type and the peak behaviour was observed only in one test

213 at 80 kPa of normal stress. The vertical displacement behaviour (Figure 7b) is similar

214 to that at 5°C; under normal stress of 80 kPa and 40 kPa, soil tends to contract at the

215 beginning and it dilates afterwards, while under lower normal stresses it tends to  
216 dilate from the beginning. The shear strength envelope is shown in Figure 7c. A very  
217 good agreement between tests under the same normal stress value could be  
218 detected at 5, 10 and 40 kPa. Friction angle is equal to  $35^\circ$  and soil is almost  
219 cohesionless.

220  
221 The results of tests at  $40^\circ\text{C}$  are exhibited in Figure 8. Similar observations to that at  
222  $5^\circ\text{C}$  and  $20^\circ\text{C}$  can be derived: discrepancy on the vertical displacement/horizontal  
223 displacement curves (Figure 8b); good repeatability on the peak strength/normal  
224 stress plot (Figure 8c); a linear correlation between the shear strength and the  
225 normal stress with a friction angle of  $35^\circ$  and a zero cohesion.

226  
227 Results on clay and clay/concrete interface at  $5^\circ\text{C}$  are shown in Figure 9. In Figure  
228 9a, clay/concrete interface shows a softening behaviour after the peak, while the  
229 shear stress increases continuously for clay. At a given normal stress, the shear  
230 stress/displacement curves of the two cases are quite similar before the peak.  
231 Results on vertical displacement versus horizontal one are shown in Figure 9b. For  
232 both clay and clay/concrete interface tests, under 40, 80 and 100 kPa, the soil shows  
233 a contracting trend while a dilating phase could be detected at lower stresses.  
234 Vertical displacement of clay is almost twice higher than that observed on  
235 clay/concrete interface under the same normal stress. Peak and ultimate shear  
236 strength of clay and that of clay/concrete interface are shown in Figure 9c. The  
237 results show that the strength envelope of clay situates above that of clay/concrete  
238 interface.

239

240 Results at 20°C are shown in Figure 10. The same observation as at 5°C (Figure 9a)  
241 is valid for Figure 10a. In addition, the fragile failure type of clay/concrete interface is  
242 more pronounced under normal stress values of 40, 80 and 100 kPa. Figure 10b  
243 shows that the vertical displacement of clay/clay is about twice higher than that of  
244 clay/concrete interface. At 40, 80 and 100 kPa of normal stress the soil volume tends  
245 to contract while it dilates at lower normal stresses. Peak and ultimate shear strength  
246 envelopes are shown in Figure 10c. As at 5°C, the ultimate shear strength of  
247 clay/concrete interface, at the same normal stress, is approximately 10% lower than  
248 that of clay.

249

250 Results on shear stress versus horizontal displacement of clay and that of  
251 clay/concrete interface at 40°C are exhibited in Figure 11a. As in the cases at 5°C  
252 and 20°C, the fragile type failure is observed for clay/concrete interface while a  
253 ductile type is observed for clay. Results on vertical displacement versus horizontal  
254 at 40°C are shown in Figure 11b. In both clay/concrete interface and clay/clay tests,  
255 under 40, 80 and 100 kPa, sample tends to contract during the shear process while  
256 dilation is observed at smaller normal stresses. The difference between the shear  
257 envelope of clay and the peak-strength envelope on clay/concrete interface is quite  
258 small at 40°C (Figure 11c).

259

260 In order to evaluate the effect of temperature on shear strength parameters (friction  
261 angle and cohesion), all the results obtained are shown in Figure 12. It should be  
262 noted that the effect of temperature on the friction angle is quite small and the trend  
263 is not clear (Figure 12a). For sand, the friction angle decreases slightly from 5°C to  
264 20°C, while in the range of 20°C and 40°C it does not change. Effect of temperature

265 on the friction of angle of clay and the ultimate friction angle of clay/concrete interface  
266 is similar; it slightly increases from 5°C to 20°C and decreases from 20°C to 40°C.  
267 The friction angle of clay is higher than the peak-strength friction angle of  
268 clay/concrete (except at 40°C). The cohesion measured on clay and clay/concrete  
269 interface is quite small, few kPa (Figure 12b) with small variation between 5°C and  
270 40°C.

271

## 272 **Discussion**

273 All the tests on sand have been duplicated. The results show good repeatability in  
274 terms of shear stress versus horizontal displacement. That allows obtaining reliable  
275 results in terms of shear strength. Nevertheless, the repeatability in terms of vertical  
276 displacement versus horizontal one is less obvious. Note that in direct shear test,  
277 only a very thin layer of soil (less than 1 mm, corresponding to the distance between  
278 the two halves of the box) is subjected to shearing. Actually, the vertical  
279 displacement is related to the volume change of the sheared zone but the thickness  
280 of this latter can vary from one test to the other. For the tests on clay and  
281 clay/concrete interface that are more time consuming, only one test has been  
282 conducted at each temperature and normal stress. The relationship between the  
283 shear strength and the normal stress can be well correlated with a linear function,  
284 which allows determining the friction angle and the cohesion. These observations  
285 show equally the reliability of the obtained results.

286

287 In order to better analyse the effect of temperature on soils friction angle, the results  
288 of the present work are plotted together with that obtained from other works in the  
289 same figure (Figure 13). The results from the existing works show that the effect of

290 temperature on soils is quite small. In addition, at higher temperature, the friction  
291 angle can be higher in some cases and lower in other ones. These observations are  
292 similar to that obtained in the present work.

293

294 The results on clay/concrete interface show a softening of the shear strength during  
295 shearing. In addition, the results indicate that the peak-strength friction angle of the  
296 clay/interface is slightly lower than that of clay (except at 40°C). As shown by  
297 previous works (Tsubakihara and Kishida 1993; Rouaiguia 2010; Taha and Fall  
298 2013) the interface behaviour is dependent on the surface roughness. After  
299 Rouaiguia (2010), the relatively plane surface of concrete makes clay particles  
300 reorient easily once the maximum shear strength is reached. The particles would  
301 then be aligned in the developed sheared zone and the shear stress decreases. In  
302 the present work, vertical settlement of the clay sample was about twice of that of  
303 clay/concrete. That can be explained by the fact that the thickness of the sheared  
304 zone in clay/clay tests (distance between the two halves of the box) would be twice  
305 that of the clay/concrete interface tests (half of the distance between the two halves  
306 of the box).

307

308 In the works of Di Donna and Laloui (2013) and Di Donna et al. (2015) on  
309 clay/concrete interface, the shear resistance at 50°C is higher than that at 20°C. The  
310 interface friction angle reduces slightly at high temperature but the most significant  
311 thermal effect is found to be an increase of the cohesion. This was explained by the  
312 thermal consolidation of the clay during heating. In the present study, all the samples  
313 have been pre-consolidated to 100 kPa of vertical stress and heated to 40°C prior to  
314 the application of the initial conditions (lower stress and temperature between 5°C

315 and 40°C). This procedure allows having soil sample at similar void ratio for all the  
316 tests. For this reason, the effect of temperature on the clay/concrete interface, which  
317 is mainly related to thermal consolidation, is negligible. In the work of Murphy and  
318 McCartney (2014), the tests were performed on unsaturated soil and the effect of  
319 temperature on the shear properties was not significant.

320

## 321 **Conclusions**

322 Shear behaviour of sand, clay and clay/concrete interface at various temperatures  
323 (5°C, 20°C, and 40°C) was investigated through direct shear tests. The following  
324 conclusions can be drawn:

- 325 - The shear stress behaviour of sand and clay show a hardening behaviour  
326 while that of clay/concrete interface show a softening one.
- 327 - At the same normal stress, the peak shear strength of clay/concrete interface  
328 is smaller than the shear strength of clay.
- 329 - The effect of temperature (in the range of 5°C – 40°C) on the shear strength of  
330 sand, clay and clay/concrete interface is negligible.

331 These findings would be helpful in designing thermoactive geostructures where the  
332 range of applied temperatures is similar and the effect of heating/cooling cycles on  
333 the shear strength at soil/structure interface might be significant.

334

## 335 **Acknowledgement**

336 This work is funded by the French National Research Agency through the project  
337 PiNRJ “Geotechnical aspects of foundation energy piles” – ANR 2010 JCJC 0908 01.  
338 This support is gratefully acknowledged. The authors would especially like to thank  
339 Dr. Alain Le Kouby and Mr. Jean-Louis Tacita for their technical support.

340

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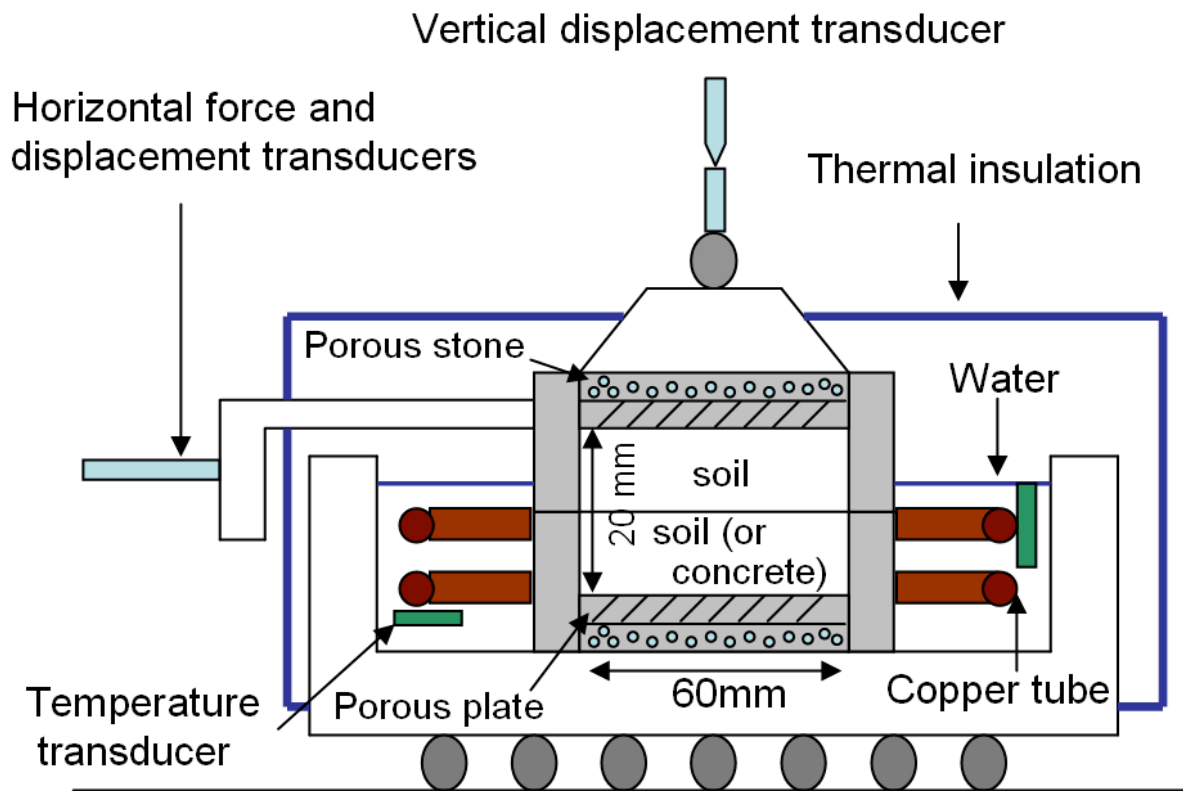
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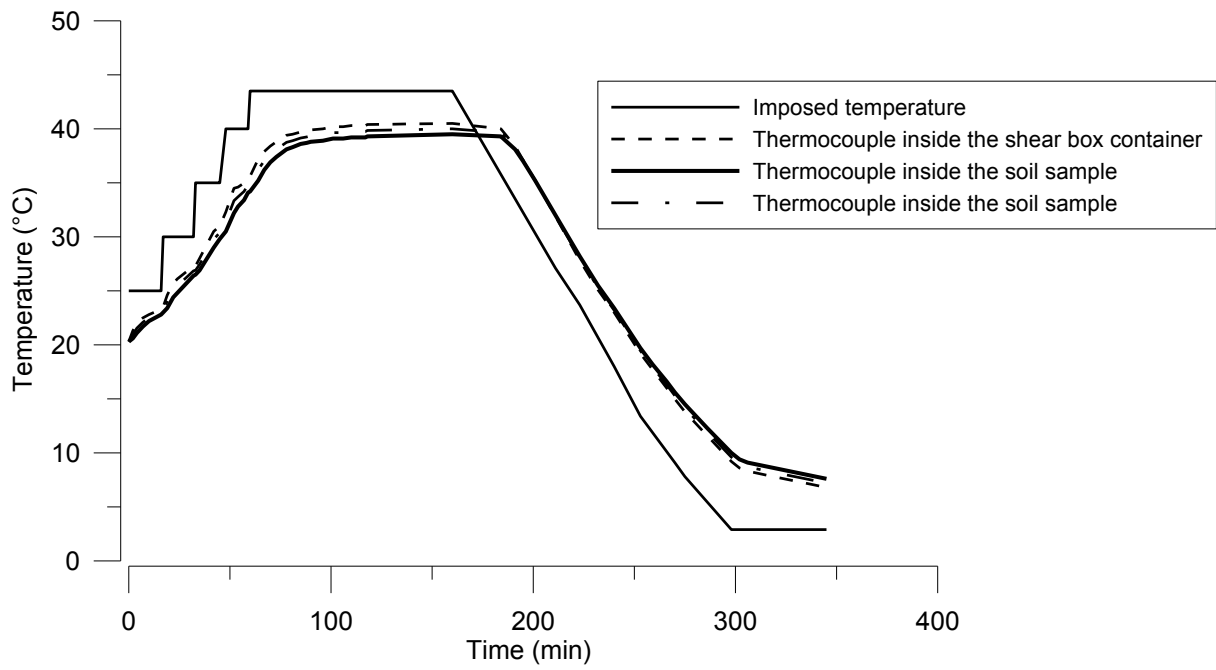
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455 **Figure 1. Direct shear apparatus with temperature control system**

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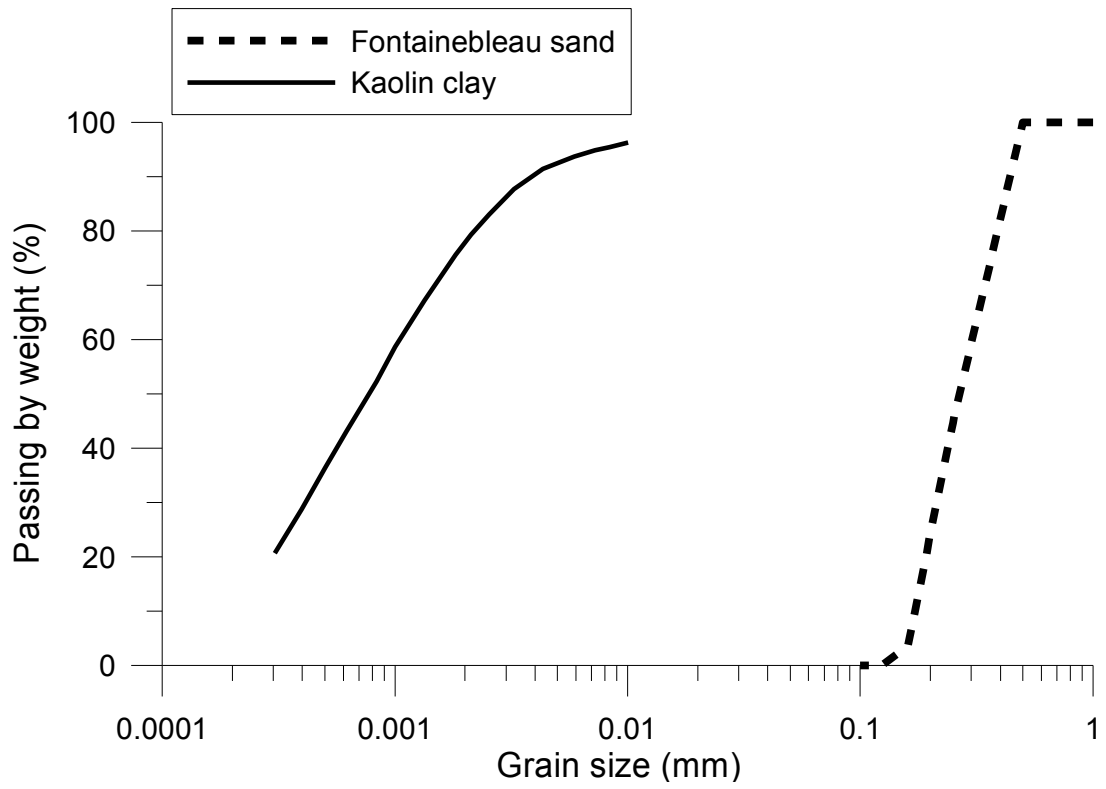
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460 **Figure 2. Results of preliminary tests for checking temperature homogeneity in the system.**

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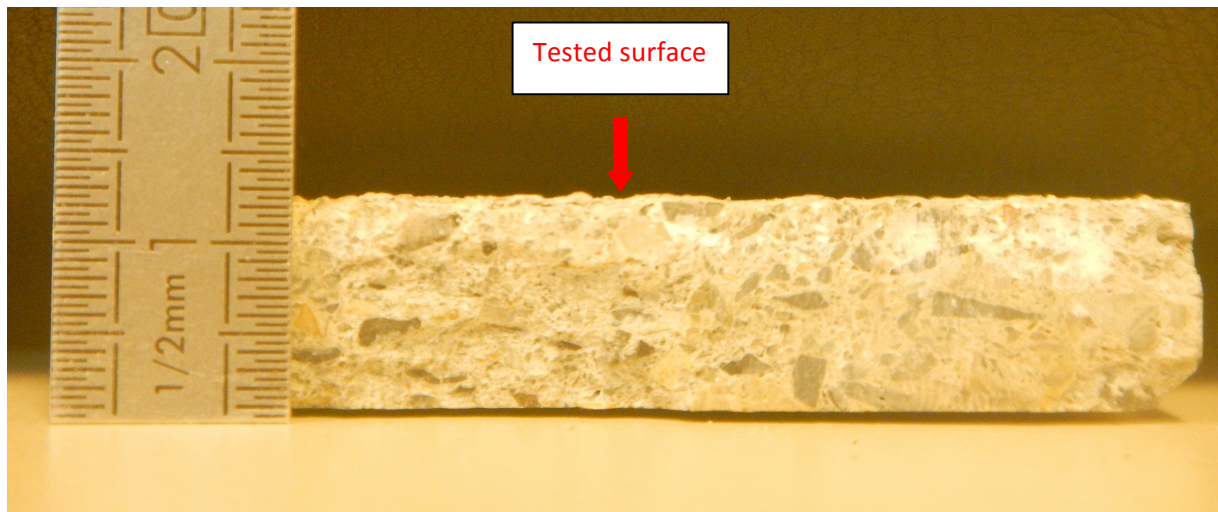
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464 Figure 3. Grain size distribution curves of Fontainebleau sand and Kaolin clay

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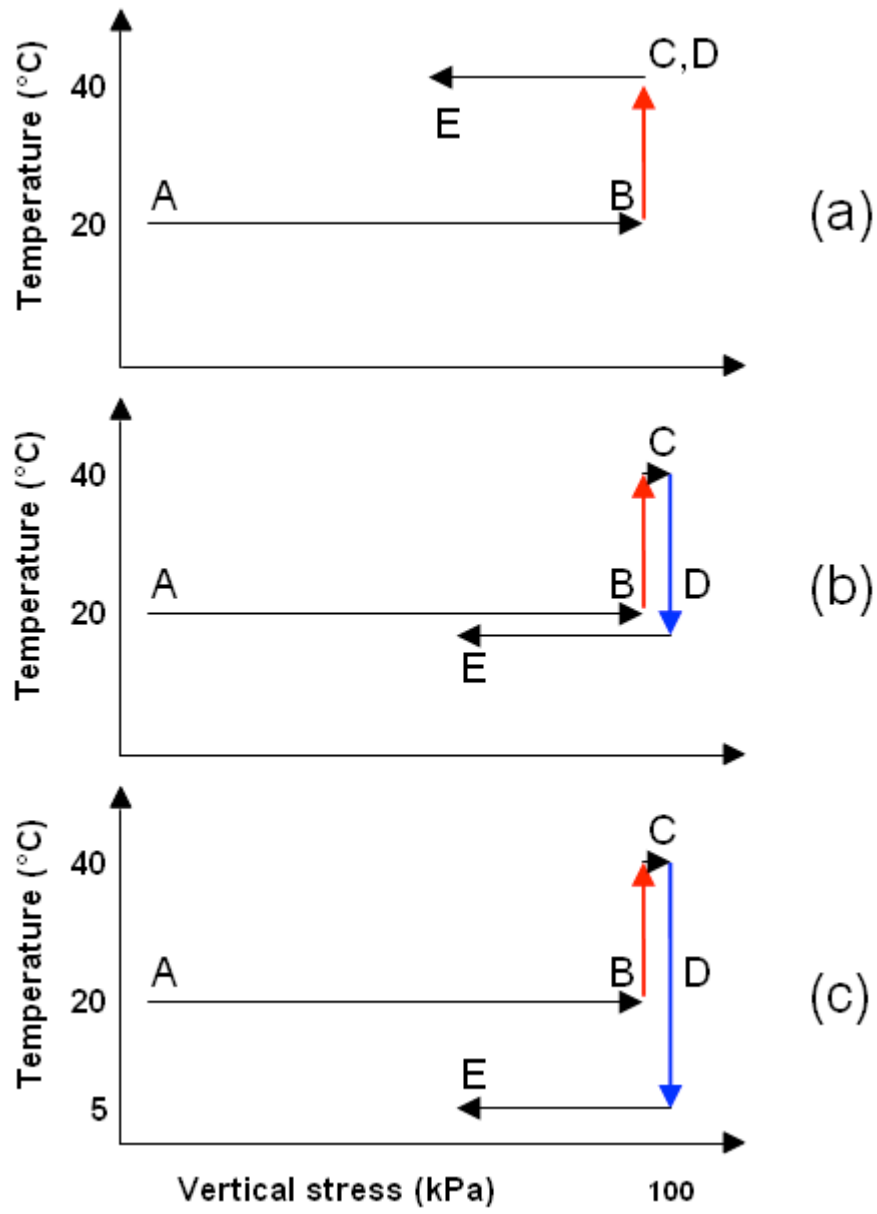
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469 Figure 4. Concrete piece used for studying clay/concrete interface

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472 **Figure 5. Thermo-mechanical paths: (a) tests at 40°C; (b) tests at 20°C; (c) tests at 5°C**

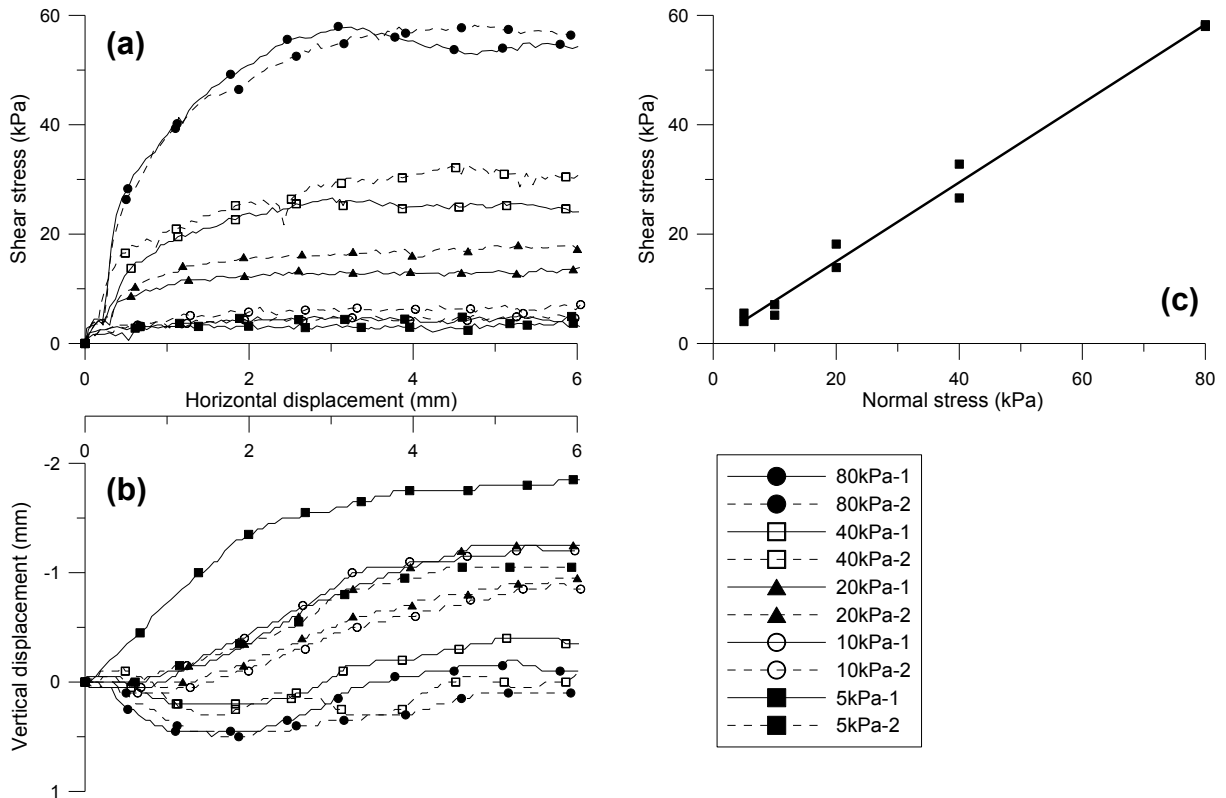
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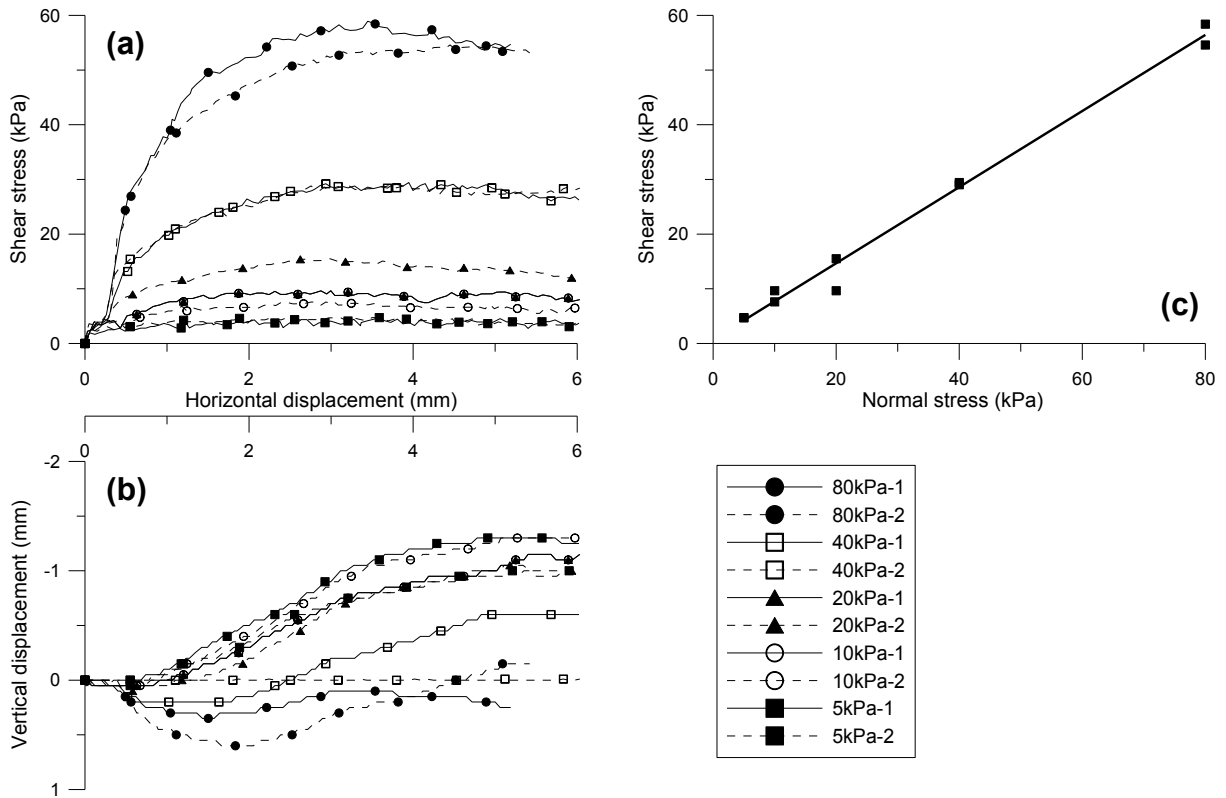
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**Figure 6. Experimental results on sand at 5°C: (a) Shear stress versus horizontal displacement; (b) Vertical displacement versus horizontal displacement; (c) Shear strength envelope**



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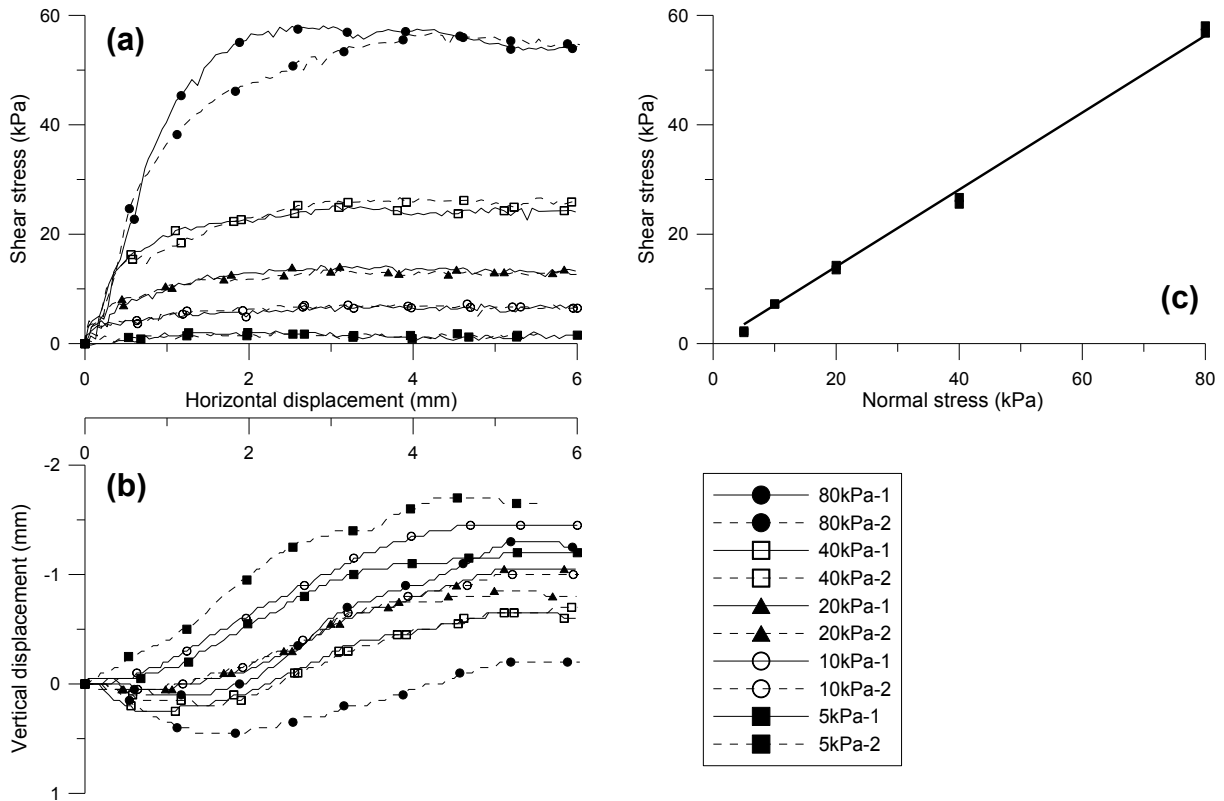
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485 **Figure 7. Experimental results on sand at 20°C: (a) Shear stress versus horizontal**  
 486 **displacement; (b) Vertical displacement versus horizontal displacement; (c) Shear strength**  
 487 **envelope**

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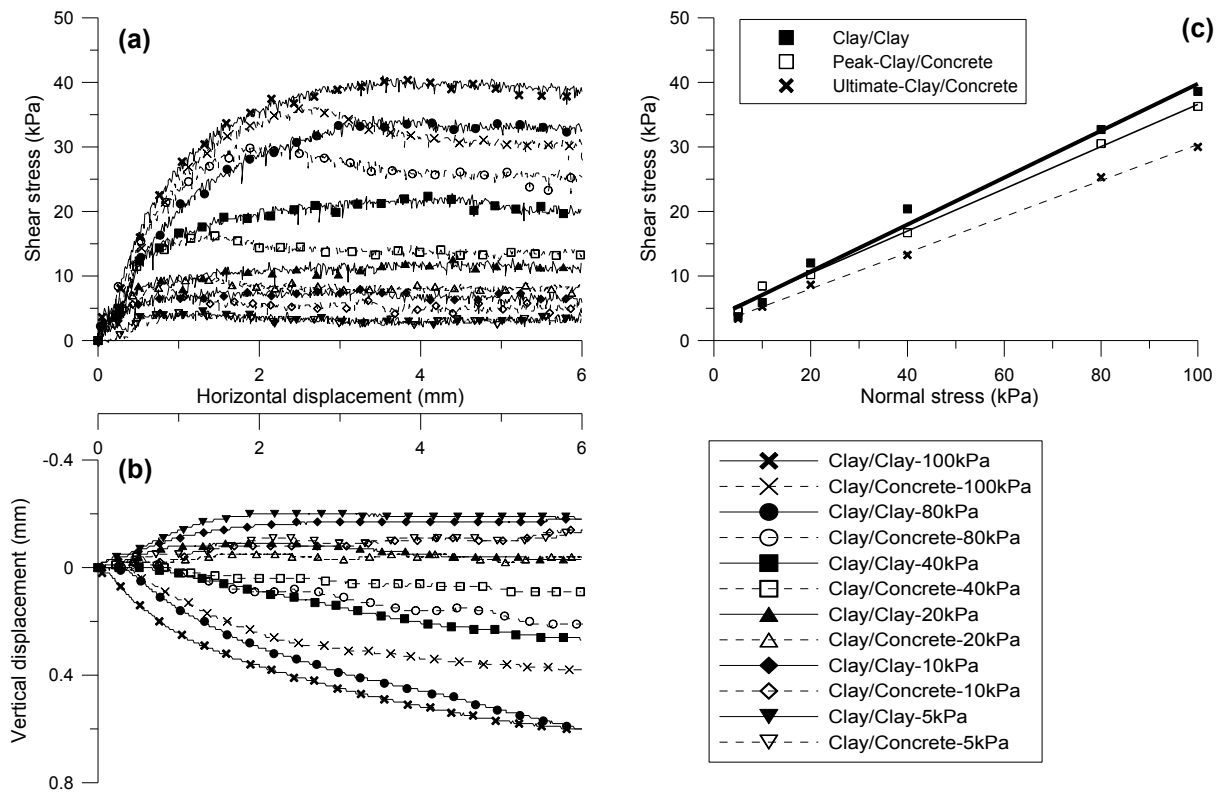
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493 **Figure 8. Experimental results on sand at 40°C: (a) Shear stress versus horizontal**  
 494 **displacement; (b) Vertical displacement versus horizontal displacement; (c) Shear strength**  
 495 **envelope**

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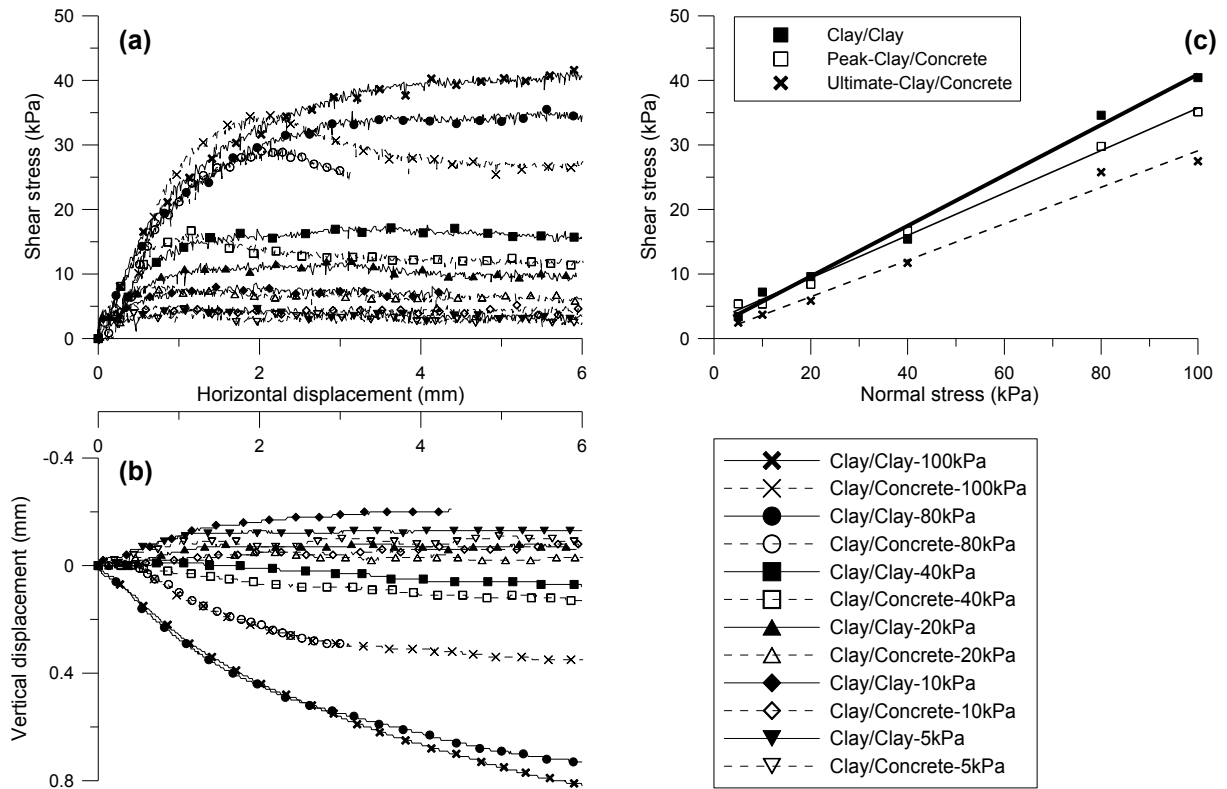


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502 **Figure 9. Experimental results on clay and clay/concrete interface at 5°C: (a) Shear stress**  
 503 **versus horizontal displacement; (b) Vertical displacement versus horizontal displacement;**  
 504 **(c) Shear strength envelope**

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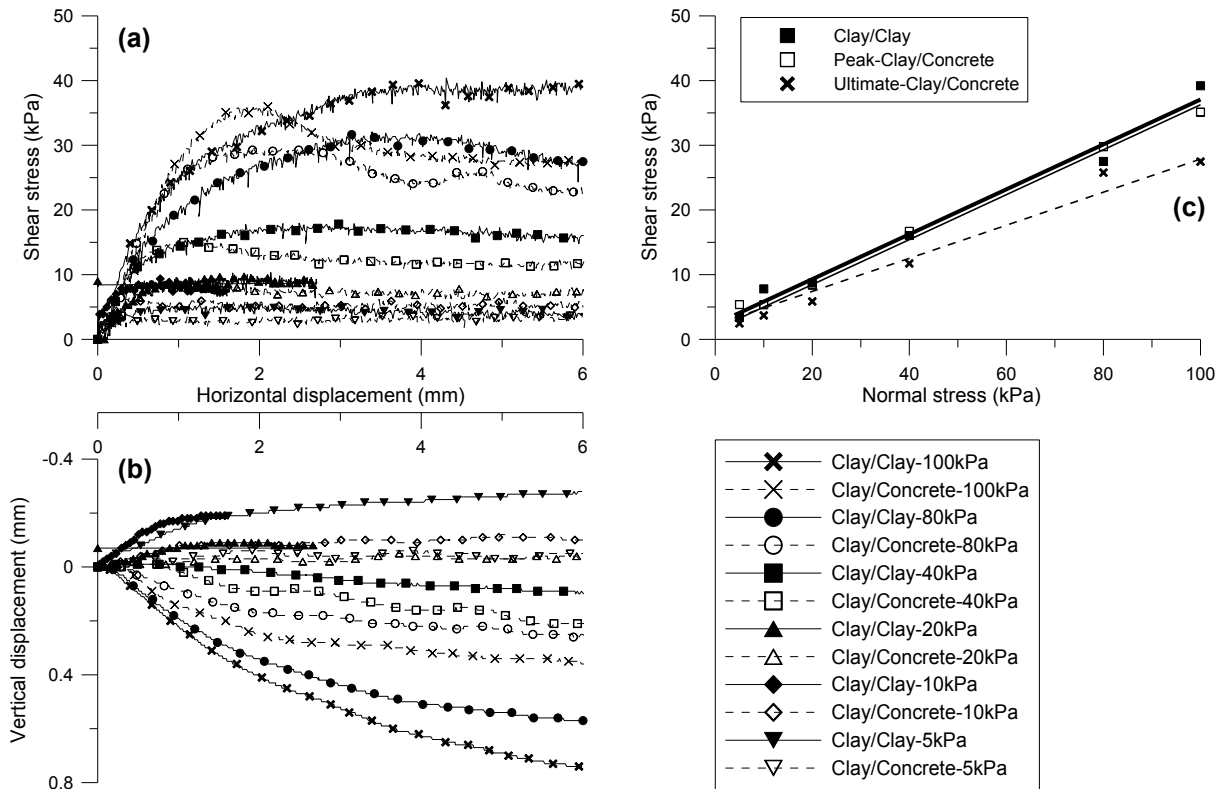
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508 **Figure 10. Experimental results on clay and clay/concrete interface at 20°C: (a) Shear stress**  
 509 **versus horizontal displacement; (b) Vertical displacement versus horizontal displacement;**  
 510 **(c) Shear strength envelope**

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515 **Figure 11. Experimental results on clay and clay/concrete interface at 40°C: (a) Shear stress**  
 516 **versus horizontal displacement; (b) Vertical displacement versus horizontal displacement;**  
 517 **(c) Shear strength envelope**

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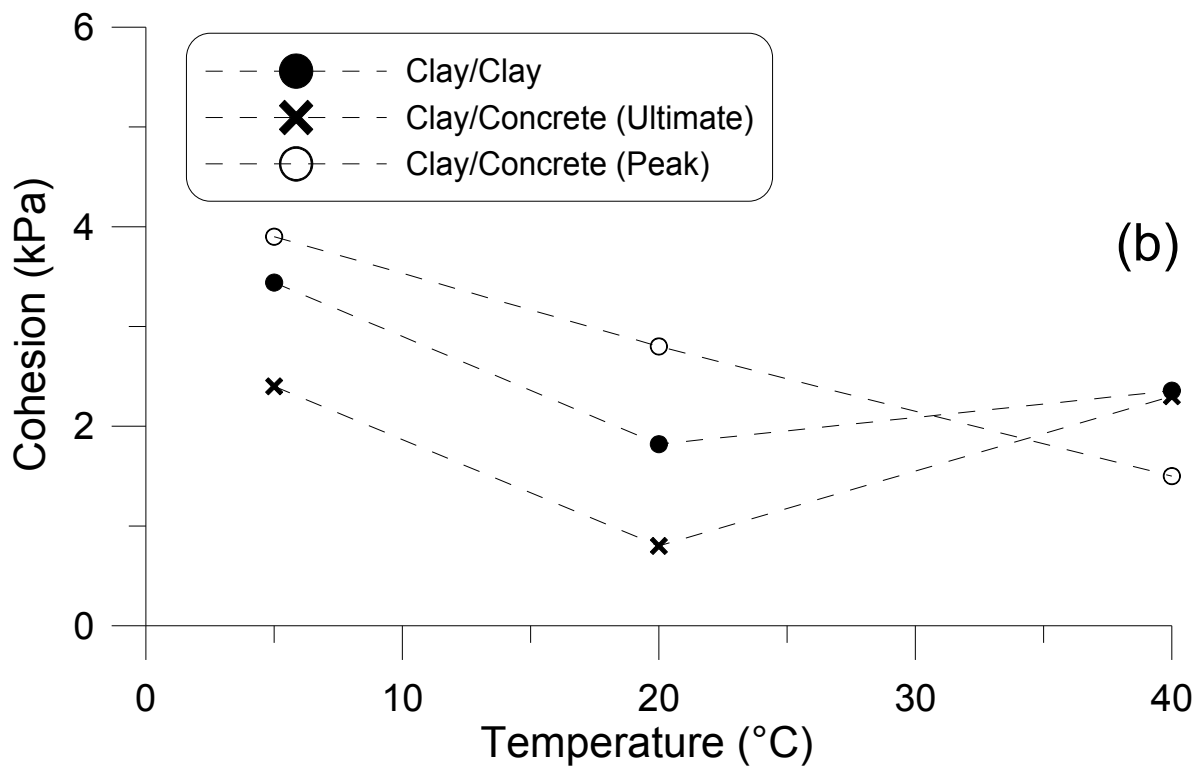
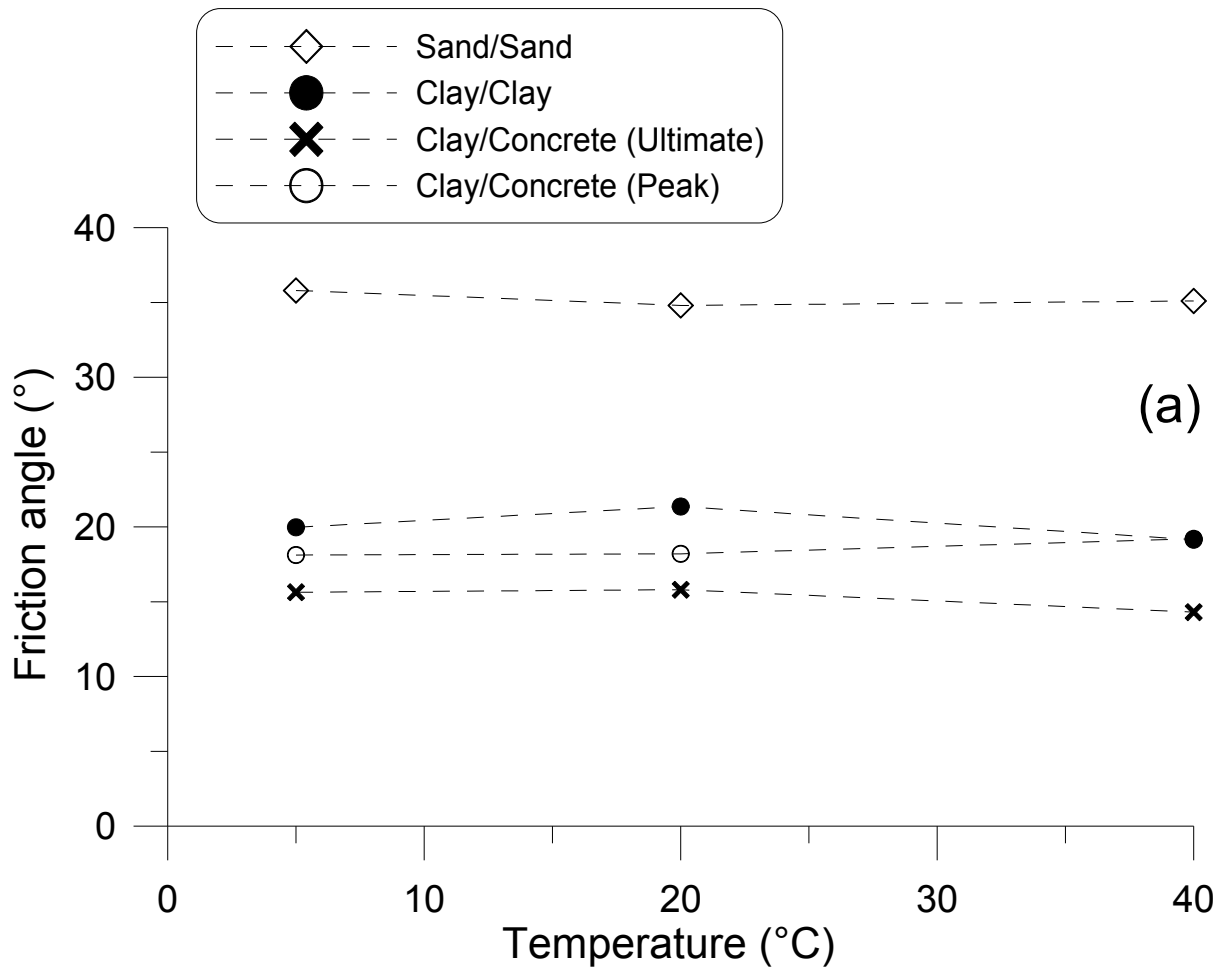
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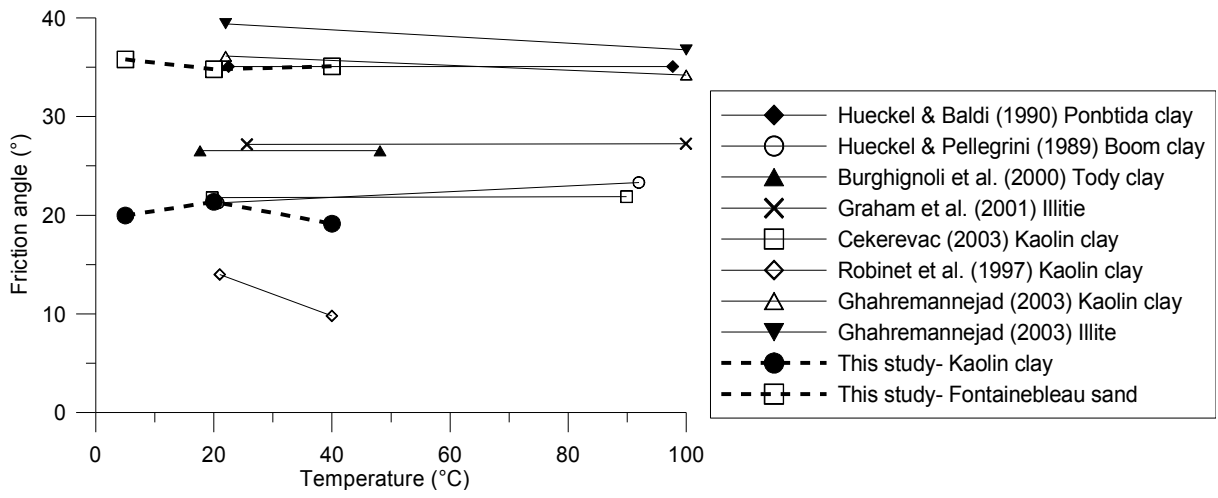


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526 **Figure 12. Effect of temperature on (a) friction angle and (b) cohesion**

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532 **Figure 13. Effect of temperature on friction angle**

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