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## Developing a Sample Preparation Approach to Study the Mechanical Behavior of Unsaturated Fine/Coarse Soil Mixture

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1 Developing a sample preparation approach to study the mechanical behaviour  
2 of unsaturated fine/coarse soil mixture

3

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20

21 **Abstract**

22 An interlayer soil was identified in the conventional French railway substructure,  
23 corresponding to a mixture of fine soils and coarse grains. As the overall mechanical  
24 behaviour of the interlayer soil can be conditioned by the microstructure of the fine soils, for  
25 the laboratory testing, it is important to develop an appropriate protocol for the sample  
26 preparation by compaction, which allows this microstructure effect to be minimised. In this  
27 study, two sample preparation approaches were considered for a fine/coarse mixture, with  
28 two distinct volumetric contents of coarse grains  $f_v$  (volumetric ratio of coarse grain to total  
29 sample). The microstructure of fine soils was investigated using mercury intrusion  
30 porosimetry, and its effect on the overall mechanical behaviour was examined through  
31 monotonic triaxial tests. Results showed that while compacted dry of optimum, the fine soils  
32 exhibited a bi-modal porosity microstructure. By contrast, while compacted wet of optimum,  
33 the fine soils exhibited a uni-modal porosity microstructure. When  $f_v = 10\%$ , the sample was  
34 characterised by a fine matrix macrostructure with coarse grains floating in it. In that case,  
35 strong effect of the microstructure of fine soils on the overall mechanical behaviour was  
36 identified. On the contrary, when  $f_v = 35\%$ , the sample was characterised by a coarse grain  
37 skeleton. In that case, very limited microstructure effect of fine soils on the overall  
38 mechanical behaviour was observed. Thus, while preparing samples of unsaturated  
39 fine/coarse soil mixture by compaction to study the overall mechanical behaviour, it is  
40 important to account for the  $f_v$  value. At low  $f_v$ , the compaction at different water contents is  
41 to be avoided because of the significant effect of microstructure of fines. On the contrary, at

42 high  $f_v$ , the samples at different water contents can be prepared by compacting the mixture at  
43 the desired water contents.

44 **Keywords:** interlayer soils; volumetric contents of coarse grains; microstructure;  
45 compaction; shear strength

46

47

48 INTRODUCTION

49 Most French conventional railway tracks were constructed by putting ballast directly on the  
50 subgrade. Due to the penetration of ballast and subgrade under the effect of train circulation  
51 over years, an interlayer of ballast/subgrade soil was created. Considering its high dry  
52 density ( $2.4 \text{ Mg/m}^3$ ) and high bearing capacity (Trinh 2011), the French railway company  
53 (SNCF) decided to keep it as part of the substructure in the national track renewal program  
54 (Cui et al. 2014).

55 The coarse grains in the interlayer soil were not uniformly distributed, with a content  
56 decreasing over depth. For the upper part, the effects of fine content and water content were  
57 studied by monotonic and cyclic triaxial tests (Trinh et al. 2012; Cui et al. 2013, 2014;  
58 Duong et al. 2013, 2014, 2016; Lamas-Lopez et al. 2015, 2016). In order to extend the study  
59 to the whole interlayer, Wang et al. (2017, 2018a, 2018b) and Qi et al. (2019) worked on  
60 compacted fine/coarse soil mixture at different volumetric contents of coarse grains,  $f_v$   
61 (volumetric ratio of coarse grain to total sample). Results revealed that there was a  
62 characteristic  $f_{v\text{-cha}}$  value, below which the mixture was characterised by a fine matrix with  
63 coarse grains floating in it, while beyond which the mixture was characterised by a coarse  
64 grain skeleton.

65 It is worth noting that in the previous studies, the fine soil state was fixed at the  
66 optimum water content and maximum dry density in order to fix the soil suction for all  
67 samples. This is obviously not the case in field conditions where suction varies with  
68 variations of water content. Thus, it is important to extend the study to the effect of water

69 content. A challenging question arises in that case for the preparation of samples: may the  
70 samples be prepared by directly compacting the mixture at different desired water contents?

71 Previous studies revealed significant difference in microstructure of fine-grained soils  
72 compacted at different remolding water contents and the strong effect of soil microstructure  
73 on the overall hydro-mechanical behaviour of fine-grained soils. Through scanning electron  
74 microscope (SEM) and mercury intrusion porosimetry (MIP), a bi-modal porosity  
75 microstructure with well-developed aggregates was observed on the dry side of optimum,  
76 while a uni-modal porosity microstructure characterised by a global fine matrix was  
77 identified on the wet side of optimum (Diamond et al. 1970; Delage et al. 1996). The plastic  
78 limit  $w_p$  (or PL) can be considered as the critical water content separating the aggregate  
79 microstructure from matrix microstructure (Ahmed et al. 1974). For the bi-modal porosity  
80 microstructure, changes in inter-aggregate voids were dominant during compression, while  
81 changes in intra-aggregate pores were dominant during saturation and drying (Li and Zhang  
82 2009; Zhang and Li 2010; Zhang et al. 2018). Through changes of small shear modulus and  
83 suction with remolding water content, Zhang et al. (2017) found that when the water content  
84 was higher than the optimum one, the total suction controlled the soil stiffness. By contrast,  
85 when the water content was lower than the optimum one, it was the contact surface between  
86 aggregates that controlled the soil stiffness.

87 In this study, in order to address the question about the possible effect of the  
88 microstructure of fine soils on the overall mechanical behaviour of the fine/coarse soil  
89 mixture, two different volumetric contents of coarse grains,  $f_v$ , were considered: 10% and  
90 35%, representing a fine matrix macrostructure and a coarse grain skeleton microstructure,

91 respectively, according to Wang et al. (2017, 2018a, 2018b). The target water contents  $w_f$  for  
92 the fine soil were  $w_1 = 11\%$  ( $S_r = 62\%$ ) and  $w_2 = 16\%$  ( $S_r = 91\%$ ), representing the dry and  
93 wet sides of optimum water content of fine soil ( $w_{opt-f} = 13.7\%$ ), respectively. Two different  
94 approaches were adopted to prepare the samples at the target water contents  $w_f$ . The first  
95 approach was to compact at the optimum water content of fines  $w_{opt-f} = 13.7\%$ . Then, the  
96 sample was dried or wetted to reach the target water content  $w_f$ . The second approach was to  
97 directly compact the sample at the target water content  $w_f$ . Mercury intrusion porosimetry  
98 was applied to study the microstructure of fine soils and monotonic triaxial tests were  
99 performed to investigate the overall mechanical behaviour. The results obtained allowed the  
100 effect of sample preparation on the overall mechanical behaviour to be clarified for  
101 unsaturated fine/coarse soil mixtures.

102

## 103 MATERIALS AND METHODS

### 104 *Sample preparation approaches*

105 The materials used by Wang et al. (2018a) were adopted in this study: nine different  
106 commercial soils were mixed to constitute the fine soils (Fig. 1) and micro-ballast (Fig. 2)  
107 was prepared using three granular soils by following the similitude method (Wang et al.  
108 2018a). The reconstituted fine soil and micro-ballast can be observed in Fig. 3. The values of  
109 specific gravity  $G_s$  of fine soil and micro-ballast were 2.68 and 2.67, respectively. The liquid  
110 limit and plasticity index of the fine soils are 32% and 20%, respectively (Fig. 4). The  
111 standard proctor compaction curve was determined following ASTM D698-12, *Standard*  
112 *test methods for laboratory compaction characteristics of soil using standard effort*, for the

113 reconstituted fine soils (Fig. 5), defining an optimum water content  $w_{\text{opt-f}} = 13.7\%$  and a  
114 maximum dry density  $\rho_{\text{dmax-f}} = 1.82 \text{ Mg/m}^3$ .

115 For the preparation of fine/coarse soil mixture samples at target water contents  $w_t$ , two  
116 different approaches were considered (Fig. 5): in the first approach, the fine soil was  
117 prepared at optimum water content  $w_{\text{opt-f}} = 13.7\%$ , then stored in hermetic container for 24 h  
118 for moisture homogenization. The fine/coarse soil mixture was then prepared by mixing the  
119 fine soil and the micro-ballast to reach the desired  $f_v$  value, with the pre-determined mass of  
120 fine soil and coarse grains (see more details in Wang et al. 2018a). The soil mixture under  
121 different  $f_v$  values were compacted in three layers to reach the sample size of 100 mm  
122 diameter and 200 mm height, with the equal amounts of fine soil and coarse grains for each  
123 layer. The photographs of the compacted samples at different  $f_v$  values are presented in Fig. 6.  
124 The compacted sample was then covered by plastic film and conserved for 24 h prior to  
125 drying or wetting to reach the target fine water content ( $w_1 = 11\%$  on the dry side or  $w_2 =$   
126  $16\%$  on the wet side). It is worth noting that while controlling the fine content, all water was  
127 considered as being contained in the fines. Because a too fast drying process would give rise  
128 to sample damage by fissuring, a milder drying method was adopted: the sample was  
129 exposed to air for 1 h each time, and then covered with plastic film for moisture equilibration.  
130 The time of equilibration needed was determined through the measurements of suctions and  
131 water contents in three positions: in the center, at  $\frac{1}{2} r$  and  $r$ ,  $r$  being the radius of the sample.  
132 Note that the suction was determined using the chilled-mirror dew-point technique (Leong et  
133 al. 2003). Results showed that at least 7 h was needed to reach reasonable equilibrium in  
134 terms of suction and water content (Table 1). In the case of wetting process, 10 g water was



135 sprayed on the sample each time prior to covering it with plastic film for equilibration. The  
136 same equilibration time of at least 7 h was adopted. In the second approach, water was  
137 simply added into the fine soil to reach the target water content  $w_1 = 11\%$  on the dry side or  
138  $w_2 = 16\%$  on the wet side. Micro-ballast was then added to reach the desired  $f_v$  values. The  
139 mixture samples were prepared by compaction to reach the size of 100 mm diameter and  
140 200 mm height.

141 As shown in Table 2, the first approach was applied to Test 1, Test 3, Test 5, and Test 7,  
142 with all tests duplicated. The second approach was applied to Test 2, Test 4, Test 6, and Test  
143 8, with only Test 2 duplicated.

#### 144 *Monotonic triaxial tests*

145 The mechanical behaviour of fine/coarse soil mixture was investigated by performing  
146 monotonic triaxial tests under drained conditions. After installation of the sample, no  
147 saturation procedure was applied. A confining pressure  $\sigma_3 = 30$  kPa was applied in all tests,  
148 which corresponded to the average horizontal stress estimated in the field under the effect of  
149 train loading by considering the Poisson's ratio and the depth of interlayer soil (Duong et al.  
150 2016). For the samples at  $w_1 = 11\%$  ( $S_r = 62\%$ ), after application of a confining pressure  $\sigma_3 =$   
151 30 kPa, they were sheared directly because only air was expected to be expelled, which was  
152 normally quite fast. However, for the samples at  $w_2 = 16\%$  ( $S_r = 91\%$ ), after application of  
153 the same confining pressure  $\sigma_3 = 30$  kPa, one night was waited prior to shearing because in  
154 that case pore water pressure could be generated. In order to ensure the full dissipation of  
155 pore water pressure during shearing, a shearing rate as low as 0.1 mm/min was adopted  
156 based on the parameter  $t_{90}$  (time for 90% consolidation) obtained from a separate

157 consolidation test on a saturated sample (ASTM D7181-11, *Standard Test Method for*  
158 *Consolidated Drained Triaxial Compression Test for Soils*). Note that the same shearing rate  
159 was adopted by Trinh et al. (2011) in the triaxial tests on the mixture of ballast  
160 grains/subgrade soil under unsaturated and saturated conditions. The tests ended either when  
161 the deviator stress reached the peak value or when the axial strain reached 15% in case of  
162 absence of peak deviator stress (ASTM D7181-11).

163 As shown in Table 2, two volumetric contents of coarse grains were considered:  $f_v =$   
164 10% and  $f_v = 35\%$ , representing a fine matrix macrostructure and a coarse grain skeleton  
165 microstructure, respectively. Test 1 to Test 4 were conducted at  $f_v = 10\%$ , while Test 5 to  
166 Test 8 were conducted at  $f_v = 35\%$ . Note that Test 1', Test 2', Test 3', Test 5' and Test  
167 7' were duplicated tests of Test 1, Test 2, Test 3, Test 5 and Test 7, respectively. As shown in  
168 Fig. 5, the first approach was applied to Test 1, Test 5 on samples dried to  $w_1 = 11\%$ , and to  
169 Test 3, Test 7 on samples wetted to  $w_2 = 16\%$ . The second approach was applied to Test 2  
170 and Test 6 on samples at  $w_1 = 11\%$ , to Test 4 and Test 8 on samples at  $w_2 = 16\%$ .

#### 171 *Mercury intrusion porosimetry (MIP)*

172 In order to study the microstructure patterns of fine soils contained in the samples with two  $f_v$   
173 values (10% and 35%) and two  $w$  values (11% and 16%), after performing the monotonic  
174 triaxial tests, fine soils at the positions far from the shear band were taken and prepared by  
175 freeze-drying method for microstructure observation. In the freeze drying, fine soils were cut  
176 into small pieces of about 1g each and then immersed into liquid nitrogen under vacuum at  
177 the freezing point ( $-210\text{ }^\circ\text{C}$ ). After that, the frozen samples were transferred into the chamber  
178 of a freeze dryer for 24 h, enabling the ice to be eliminated by sublimation. This procedure

179 allowed the sample microstructure disturbance to be minimized, guaranteeing the quality of  
180 MIP tests (Cui et al. 2002; Delage et al. 2006).

181 In this study, five MIP tests were performed on the specimens at  $f_v = 10\%$ : three at  $w_1 =$   
182 11% (Test 1, Test 2 and duplicated Test 2') and two at  $w_2 = 16\%$  (Test 3 and Test 4). In  
183 addition, five MIP tests were performed on specimens at  $f_v = 35\%$ : three at  $w_1 = 11\%$  (Test 5,  
184 Test 6 and Test 6') and two at  $w_2 = 16\%$  (Test 7 and Test 8). Note that the MIP tests were  
185 labeled with the same numbers as the monotonic triaxial tests in further analysis.

186

## 187 EXPERIMENTAL RESULTS

### 188 *Shear behaviour*

189 The results from monotonic triaxial test at two different  $f_v$  values (10% and 35%) and two  
190 different water contents ( $w = 11\%$  and 16%) were presented in Figs. 7-10, with the deviator  
191 stress  $q$  and the volumetric strain  $\varepsilon_v$  plotted against the axial strain  $\varepsilon_a$ . Comparison between  
192 the duplicated tests (Test1 against Test 1', Test 2 against Test 2', Test 3 against Test 3', Test  
193 5 against Test 5' and Test 7 against Test 7') showed that the results were quite similar,  
194 showing a satisfactory repeatability.

195 Figs. 7(a)-10(a) showed the variation of deviator stress  $q$  with axial strain  $\varepsilon_a$ . It appeared  
196 from Fig. 7(a) that the deviator stress  $q$  of Test 1 (first approach) increased with the axial  
197 strain  $\varepsilon_a$  until reaching a peak deviator stress  $q_{\max} = 397$  kPa, then decreased and finally  
198 stabilized at  $q = 200$  kPa, while for Test 2 (second approach), the peak deviator stress was  
199 less pronounced and much lower ( $q_{\max} = 230$  kPa). This suggested different stress-strain  
200 behaviours of samples at  $f_v = 10\%$  and  $w_1 = 11\%$  when prepared by two different approaches.

201 It was observed from Fig. 8(a) that the higher water content ( $w_2 = 16\%$ ) led to the  
202 disappearance of peak deviator stress. Moreover, the whole stress-strain curves became  
203 almost the same with the quite close maximum deviator stresses:  $q_{\max} = 132$  kPa for Test 3  
204 (first approach) and  $q_{\max} = 115$  kPa for Test 4 (second approach), respectively, showing a  
205 clear water content effect. When the value of  $f_v$  increased to 35%, both approaches (Tests 5  
206 with the first approach and Test 6 with the second approach) gave rise to quite similar stress-  
207 strain curves with marked peaks at  $w_1 = 11\%$  (Fig. 9(a)). The peak deviator stress of Test 5  
208 was  $q_{\max} = 459$  kPa, quite close to the value of Test 6:  $q_{\max} = 490$  kPa. When the water  
209 content increased to  $w_2 = 16\%$  (Fig. 10(a)), as in the case of  $f_v = 10\%$ , no marked peak was  
210 observed. Moreover, the whole stress-strain curves became almost the same with quite close  
211 maximum deviator stresses:  $q_{\max} = 242$  kPa for Test 7 (first approach) and  $q_{\max} = 225$  kPa for  
212 Test 8 (second approach).

213 Summarizing, with two different sample preparation approaches, the stress-strain curves  
214 were different at a value of  $f_v$  as low as 10% and at a water content corresponding to the dry  
215 side of optimum ( $w_1 = 11\%$ ). On the contrary, no significant difference was observed  
216 between the two sample preparation approaches at a value of  $f_v$  as high as 35%, or at a water  
217 content corresponding to the wet side of optimum ( $w_2 = 16\%$ ).

218 Figs. 7(b) -10(b) showed the variation of volumetric strain  $\varepsilon_v$  with axial strain  $\varepsilon_a$ . In Fig.  
219 7(b) for all samples, the volumetric strain  $\varepsilon_v$  started with a contractancy stage followed by a  
220 dilatancy stage. The dilatancy appeared more pronounced for Test 1, as compared to that of  
221 Test 2. At the higher water content ( $w_2 = 16\%$ ) in Fig. 8(b), the first (Test 3) and the second  
222 (Test 4) sample preparation approaches gave rise to quite similar pure contractancy curves,

223 evidencing a significant water content effect. In the case of  $f_v = 35\%$ , all curves were  
 224 characterised by a contractancy stage followed by a dilatancy stage (Figs. 9(b) and 10(b)),  
 225 with the dilatancy much larger than that at  $f_v = 10\%$ , in particular in the case of dry side of  
 226 optimum (Fig. 9(b)). Moreover, there was little difference between the curves of the first  
 227 sample preparation approach and those of the second sample preparation approach: for both  
 228 dry side (Fig. 9(b)) and wet side (Fig. 10(b)), the curves were almost the same.

229 Overall, as for the stress-strain curves, the volumetric strain-axial strain curves also  
 230 showed different behaviours at  $f_v = 10\%$  on the dry side of optimum ( $w_1 = 11\%$ ), but quite  
 231 similar behaviours at  $f_v = 35\%$  or on the wet side of optimum ( $w_2 = 16\%$ ).

### 232 *Mechanical parameters*

233 For further analysis, four mechanical parameters were adopted, including the maximum  
 234 deviator stress  $q_{\max}$  as mentioned previously, the initial Young's modulus  $E_0$ , the Poisson's  
 235 ratio  $\nu$  and the dilatancy angle  $\psi$ . The initial Young's modulus  $E_0$  was defined as the ratio of  
 236 deviator stress to axial strain from 0% to 1% (Wang et al. 2018a; Qi et al. 2019). Based on  
 237 the volumetric strain-axial strain curve in Fig. 11, taking Test 2 for example, the Poisson's  
 238 ratio  $\nu$  and dilatancy angle  $\psi$  were determined using Eqs. (1) and (2) (Vermeer et al. 1984),  
 239 respectively:

$$240 \quad \nu = (1 - k_c)/2 \quad (1)$$

$$241 \quad \sin \psi = k_d / (-2 + k_d) \quad (2)$$

242 where  $k_c$  and  $k_d$  were the slopes of volumetric strain-axial strain curves in the contractancy  
 243 and dilatancy phases, respectively.

244 The values of four mechanical parameters for all tests were determined and then

245 presented in Table 3. As for the shear behaviour, satisfactory repeatability of test results can  
246 be observed through comparison of duplicated tests (Test1 against Test 1', Test 2 against  
247 Test 2', Test 3 against Test 3', Test 5 against Test 5' and Test 7 against Test 7').

248 At  $f_v = 10\%$  and  $w_1 = 11\%$ , the maximum deviator stress  $q_{max} = 397$  kPa and 230 kPa,  
249 the initial Young's modulus  $E_0 = 27.5$  MPa and 20.1 MPa and the dilatancy angle  $\psi = 8.05$   
250 degree and 4.01 degree were observed for Test 1 (first approach) and Test 2 (second  
251 approach) respectively. Thus, significant difference existed between Test 1 (first approach)  
252 and Test 2 (second approach). Moreover, the values of Poisson's ratio  $\nu$  were 0.23 and 0.24  
253 for Test 1 (first approach) and Test 2 (second approach) respectively, indicating little  
254 influence by the sample preparation approaches. The same observation of Poisson's ratio  $\nu$   
255 can be made when comparing Test 3 (first approach) with Test 4 (second approach), Test 5  
256 (first approach) with Test 6 (second approach), and Test 7 (first approach) with Test 8  
257 (second approach). At  $f_v = 10\%$  and  $w_2 = 16\%$ , very close values of maximum deviator stress  
258 ( $q_{max} = 132$  kPa and 115 kPa) and initial Young's modulus ( $E_0 = 5.1$  MPa and 4.5 MPa) were  
259 observed for Test 3 (first approach) and Test 4 (second approach), respectively. When the  
260 value of  $f_v$  increased to 35%, two sample preparation approaches gave quite similar values of  
261 maximum deviator stress ( $q_{max} = 459$  kPa and 490 kPa), initial Young's modulus ( $E_0 = 40.4$   
262 MPa and 41.9 MPa) and dilatancy angle ( $\psi = 17.46$  degree and 16.26 degree) for Test 5  
263 (first approach) and Test 6 (second approach), respectively. The same observation can be  
264 made when comparing Test 7 (first approach) with Test 8 (second approach).

265 Overall, two different approaches only led to different values of mechanical parameters  
266 at low  $f_v$  value ( $f_v = 10\%$ ) and on the dry side of optimum ( $w_1 = 11\%$ ), which was consistent

267 with the observation of stress-strain curves and volumetric strain-axial strain curves.

#### 268 *Microstructure of fine soils*

269 The pore size distribution (PSD) curves obtained from MIP tests were shown in Figs. 12-13,  
270 with the global fine soil void ratio ( $e = 0.47$ ) plotted. Fig. 12 (a<sub>1</sub>) showed that the final value  
271 of intruded mercury void ratio  $e_M$  was a little smaller than the global void ratio  $e$ . In addition,  
272 a typical bi-modal porosity was identified for Test 1 (first approach), Test 2 (second approach)  
273 and Test 2' (second approach) in Fig. 12 (b<sub>1</sub>), with two pore populations: micro-pores with  
274 the same size  $0.2 \mu\text{m}$ , and macro-pores with a size  $3 \mu\text{m}$  for Test 1 and  $2 \mu\text{m}$  for Test 2 and  
275 Test 2'. Note that the PSD curves obtained from Test 2 (second approach) were close to that  
276 of Test 2' (second approach), showing a satisfactory repeatability of MIP tests. On the wet  
277 side ( $w_2 = 16\%$  in Figs. 12 (a<sub>2</sub>)-(b<sub>2</sub>)), quite similar uni-modal microstructures were identified  
278 for Test 3 (first approach) and Test 4 (second approach), with the same family of micro-  
279 pores at a size  $0.6 \mu\text{m}$ .

280 Figs. 13 (a<sub>1</sub>)-(b<sub>1</sub>) showed that a bi-modal porosity was observed for Test 5 (first  
281 approach), Test 6 (second approach) and Test 6' (second approach), with two pore  
282 populations: micro-pores at the same size of  $0.3 \mu\text{m}$ , and macro-pores at different sizes of  $3$   
283  $\mu\text{m}$ ,  $2 \mu\text{m}$  and  $9 \mu\text{m}$  for Test 5 (first approach), Test 6 (second approach) and Test 6'  
284 (second approach), respectively. In addition, the quantity of macro-pores of Test 5 (first  
285 approach) appeared quite limited, while that of Test 6 (second approach) and Test 6' (second  
286 approach) was much larger. Note that the fine soils with different quantity of macro-pores of  
287 Test 6 and Test 6' were taken from the same sample at  $f_v = 35\%$ , indicating the non-uniform  
288 distribution of fine soils in the coarse grain skeleton. From Figs. 13(a<sub>2</sub>)-(b<sub>2</sub>), the same uni-

289 modal microstructure with a population of micro-pores of 0.3  $\mu\text{m}$  diameter was identified for  
290 Test 7 (first approach) and Test 8 (second approach). These observations of microstructure  
291 of fine soil compacted at different water content were in full agreement with previous  
292 findings of Delage et al. (1996).

293

## 294 INTERPRETATION AND DISCUSSION

### 295 *The effect of matrix suction on sample preparation*

296 The results obtained from MIP tests showed a bi-modal porosity at  $w_1 = 11\%$  on the dry side  
297 (Fig. 12(a<sub>1</sub>) - (b<sub>1</sub>) and Fig. 13(a<sub>1</sub>) - (b<sub>1</sub>)), and a uni-modal porosity at  $w_2 = 16\%$  on the wet  
298 side (Fig. 12(a<sub>2</sub>) - (b<sub>2</sub>) and Fig. 13(a<sub>2</sub>) - (b<sub>2</sub>)). These results obtained can be explained by the  
299 effect of matrix suction on sample preparation by compaction.

300 At a water content as low as  $w_1 = 11\%$  on the dry side of optimum, fine aggregates with  
301 high matric suction inside were preserved. As a result, further compaction mainly made re-  
302 arrangement of the aggregates. This led to the existence of both small pores inside  
303 aggregates and large pores among aggregates. However, at a water content as high as  $w_2 =$   
304 16% on the wet side of optimum, the initial fine aggregates were expected to be destroyed  
305 by the water hydration or the decrease of matric suction. As a result, a fine matrix structure  
306 was expected to be formed after compaction, leading to a uni-modal pore-size distribution.

307 At the optimum water content  $w_{\text{opt-f}} = 13.7\%$ , the matric suction inside the fine  
308 aggregates was normally lower than that at  $w_1 = 11\%$ , but high enough to keep certain  
309 mechanical resistance of the aggregates. In other words, the aggregates at  $w_{\text{opt-f}} = 13.7\%$   
310 were expected to be more deformable than those at  $w_1 = 11\%$ . As a result, under the effect of



311 further compaction, less large pores were produced in the case of  $w_{\text{opt-f}} = 13.7\%$ . When  
312 drying from  $w_{\text{opt-f}} = 13.7\%$  to  $w_1 = 11\%$ , the matric suction was increased and some  
313 shrinkage was expected, enlarging the large pores a little. By contrast, when wetting from  
314  $w_{\text{opt-f}} = 13.7\%$  to  $w_2 = 16\%$ , the matric suction was decreased and some swelling was  
315 expected, decreasing the large pores a little. Even though some microstructure changes could  
316 occur during drying or wetting, it appeared that the effects of drying or wetting were much  
317 less significant than those of the remolded water content (see Figs. 12-13).

### 318 *Shear strength of soil mixture and microstructure of fine soils*

319 The results obtained from monotonic triaxial test indicated that the shear strength was  
320 different between Test 1 and Test 2 at  $f_v = 10\%$  and  $w_1 = 11\%$ , with two different sample  
321 preparation approaches. On the contrary, no marked difference of shear strength was  
322 observed between Test 3 and Test 4 at  $f_v = 10\%$  and  $w_2 = 16\%$ , even though the sample  
323 preparation approaches were also different. Moreover, quite similar shear strength was  
324 identified for Test 5 and Test 6 and for Test 7 and Test 8 at  $f_v = 35\%$ , whatever the water  
325 content values (dry side or wet side).

326 Wang et al. (2018a) showed that at  $f_v = 10\%$  (smaller than the characteristic value  $f_{v\text{-cha}}$   
327  $\approx 27\%$ ), the fine/coarse soil mixture was characterized by a fine matrix macrostructure with  
328 coarse grains floating in it. By contrast, at  $f_v = 35\%$  (larger than  $f_{v\text{-cha}} \approx 27\%$ ), the mixture  
329 was characterized by a coarse grain skeleton microstructure. As a consequence, the shear  
330 strength of Test 1 to Test 4 at  $f_v = 10\%$  was governed by the fine soils. In that case, the  
331 changes of microstructure of fine soils with compaction water content greatly affected the  
332 overall mechanical behaviours. On the dry side, bi-modal porosity existed in the samples

333 (Test 1 and Test 2 in Fig. 12(b<sub>1</sub>)), corresponding to the micro-pores within aggregates (intra-  
334 aggregate pores) and the macro-pores between aggregates (inter-aggregate pores). In that  
335 case, the inter-aggregate pores played an important role in the structure of fine soils and the  
336 assembly of aggregates governed the soil stiffness. Since the quantity of inter-aggregate  
337 pores for Test 2 was much larger than that of Test 1 (Fig. 12 (b<sub>1</sub>)), less pronounced peak  
338 deviator stress was identified for Test 2 ( $q_{\max} = 230$  kPa) as compared to Test 1 ( $q_{\max} = 397$   
339 kPa) in Fig. 7. The similar observation was made by Zhang et al. (2017) on the stiffness of  
340 fine soils with different remolding water contents: the inter-aggregate pores dominated the  
341 soil microstructure on the dry side of Proctor optimum. With the increase of water content,  
342 the increase of inter-aggregate contact surface gave rise to the increase of maximum shear  
343 modulus  $G_{\max}$  or soil stiffness. Vanapalli et al. (1996a, 1996b) also found the effect of inter-  
344 aggregate contact surface on unsaturated shear strength of compacted glacier till. The results  
345 showed that for a given matrix suction, the specimens prepared at higher water content have  
346 larger shear strength. In addition, it has been reported by several investigators that the  
347 unsaturated shear strength and soil-water retention curves were dependent on soil  
348 microstructure which was in turn dependent on the remolding water content (Delage et al.  
349 1996; Vanapalli et al. 1996a, 1996b; Birle et al. 2008).

350 By contrast, on the wet side ( $w_2 = 16\%$ ), all aggregates were destroyed and a uni-modal  
351 porosity was usually observed (Test 3 and Test 4 in Fig. 12(b<sub>2</sub>)). Thus, quite similar global  
352 mechanical behaviours were expected (Fig. 8).

353 When the value of  $f_v$  became 35%, higher than  $f_{v\text{-cha}} \approx 27\%$ , the soil microstructure was  
354 rather characterised by a coarse grain skeleton. Thus, the mechanical responses in Test 5 to

355 Test 8 at  $f_v = 35\%$  were expected to be governed by the coarse grains skeleton (Figs. 9-10),  
356 whatever the microstructure of fines – bi-modal for Test 5 and Test 6 at  $w_1 = 11\%$  (Figs.  
357 13(a<sub>1</sub>) - (b<sub>1</sub>)) and uni-modal for Test 7 and Test 8 at  $w_2 = 16\%$  (Figs. 13(a<sub>2</sub>) - (b<sub>2</sub>)). Indeed,  
358 the same shear behaviours were observed from Test 5 and Test 6 at  $w_1 = 11\%$  shown in Fig.  
359 9, and the same shear behaviours were observed from Test 7 and Test 8 at  $w_2 = 16\%$  shown  
360 in Fig. 10.

### 361 *Distribution of fine soils*

362 Comparison of the PSD curves between Test 6 and Test 6' at  $f_v = 35\%$  (Figs. 13(a<sub>1</sub>) - (b<sub>1</sub>))  
363 showed that they were not the same, even though both were of bi-modal nature. For further  
364 analysis, the PSD curve of Test 2 at  $f_v = 10\%$  was put together with those of Test 6 and Test  
365 6' at  $f_v = 35\%$  in Figs. 14(a) - (b). It appeared that the PSD curve of Test 6' was characterised  
366 by a larger value of intruded mercury void ratio ( $e_M = 0.72$ ) and a larger quantity of macro-  
367 pores, as compared with that of Test 6. The quantity of macro-pores of Test 2 was between  
368 those of Test 6 and Test 6'. This suggested two categories of fine soils in the coarse grains  
369 skeleton structure ( $f_v = 35\%$ ), namely dense fine soils in-between coarse grains (Test 6) and  
370 loose fine soils in macro-pores among grains (Test 6'). On the contrary, in the case of fine  
371 matrix macrostructure ( $f_v = 10\%$ ), fine soils were relatively uniformly distributed.

372 At  $f_v = 10\%$ , the inter-particle forces were expected to be transmitted in the fine matrix,  
373 leading to a relatively uniform void ratio of fines (Test 2, Fig. 14). The situation was  
374 different at  $f_v = 35\%$ , with two categories of fine soils. The dense fine soils located in-  
375 between coarse grains were compressed when the inter-particle forces were transmitted  
376 along the coarse grains skeleton, leading to a smaller void ratio and a smaller macro-pores

377 volume of fine soils (Test 6, Fig. 14). By contrast, the loose fine soils surrounded by coarse  
378 grains were less compressed, giving rise to a larger void ratio and a larger macro-pores  
379 volume of fine soils (Test 6', Fig. 14).

380 The results showed that the micro-pores of samples compacted dry of optimum were  
381 almost unaffected by the compaction efforts, while the macro-pores were strongly dependent  
382 on the compaction efforts. This was consistent with the observation by Miao et al. (2007)  
383 who studied the microstructure of expansive soil with varying dry densities by mercury  
384 intrusion tests: with the increase of dry density (compaction efforts), the volume of micro-  
385 pores remained constant, while that of macro-pores significantly decreased.

386 Despite the existence of two categories of fine soil at high  $f_v = 35\%$ , the overall  
387 mechanical behaviour was governed by the coarse grain skeleton. In other words, the  
388 variability of void ratio of fine soils has no effect on the overall mechanical behaviour of  
389 fine/coarse soil mixture in that case.

390

## 391 CONCLUSIONS

392 For the fine/coarse soil mixture, two sample preparation approaches were adopted: the first  
393 approach was to compact the fine/coarse soil mixture at the optimum water content of fines  
394  $w_{opt-f}$ , then dry or wet the sample to reach the target water content  $w_f$  ( $w_1 = 11\%$  on the dry  
395 side or  $w_2 = 16\%$  on the wet side). The second approach was to directly compact the  
396 fine/coarse soil mixture at the target water content  $w_f$ . Through monotonic triaxial tests and  
397 mercury intrusion porosimetry observation, the effect of microstructure of fine soils on the  
398 overall mechanical behaviours of the soil mixture was evidenced.

399 As expected, a bi-modal microstructure of fine soils was identified on the dry side and a  
400 uni-modal microstructure on the wet side, in agreement with the findings of Delage et al.  
401 (1996). According to the studies by Wang et al. (2017, 2018a, 2018b), at  $f_v = 10\%$ , the soil  
402 mixture was characterized by a fine matrix macrostructure with coarse grains floating in it,  
403 while at  $f_v = 35\%$ , a coarse grains skeleton was formed. It was observed that in the former  
404 there was a strong effect of microstructure of fine soils on the overall mechanical behaviour  
405 of the fine/coarse soil mixture, while in the latter case the effect of microstructure of fine  
406 soils became quite limited. Moreover, it was found that at  $f_v = 35\%$ , the microstructures of  
407 fine soil were not uniform, with dense fines in-between coarse grains and loose fines  
408 surrounded by coarse grains.

409 Therefore, to minimize the effect of microstructure of fine soils on the overall  
410 mechanical behaviour of soil mixture during sample preparation, at low  $f_v$  with the  
411 macrostructure defined by fine matrix, only the first sample preparation approach can be  
412 adopted for the dry side but the two approaches can be adopted for the wet side. On the  
413 contrary, at high  $f_v$  with the microstructure defined by coarse grains skeleton, the two sample  
414 preparation approaches can be adopted, whatever the remolded water content. However, this  
415 conclusion is valid only when the mechanical behaviour is addressed. It is anticipated that  
416 the hydraulic behaviour must be significantly different between dry and wet samples,  
417 whatever the  $f_v$  values, because of the different microstructures created while compacting at  
418 different water contents.

419 It is worth noting that to some extent the obtained results can be helpful in evaluating  
420 the effect of the formation process on the global mechanical behavior for the interlayer soil  
421 or the fouled ballast.

422

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425

#### 426 NOTATIONS

$e$	global void ratio of fine soils
$e_M$	intruded mercury void ratio
$E_0$	initial modulus
$f_v$	volumetric coarse grain content
$G_s$	specific gravity
$k_c$	slope of volume change curve in the contractancy phase
$k_D$	slope of volume change curve in the dilatancy phase
$q$	deviator stress
$q_{\max}$	peak deviator stress
$t_{90}$	time for 90% consolidation
$w_{\text{opt-f}}$	optimum water content of fine soils
$w_f$	water content of fine soils
$w_1$	water content of fine soils on the dry side
$w_2$	water content of fine soils on the wet side

$\varepsilon_a$	axial strain
$\varepsilon_v$	volumetric strain
$\rho_d$	dry density of sample
$\rho_{dmax-f}$	maximum dry density of fine soils
$\sigma_3$	confining pressure
$\nu$	Poisson's ratio
$\psi$	dilatancy angle

427

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Table 1. Suction and water content measured at different equilibration times for fine soils

Position	Suction (MPa)	Water content (%)	Suction (MPa)	Water content (%)
	After 6h		After 7h	
	center	0.33	12.7	0.32
1/2 r	0.24	13.5	0.35	12.8
r	0.46	13.7	0.33	13.1

Table 2. Soil properties of samples tested

Test	Sample preparation approach	$f_v$ (%)	Target	Target	Target	Measured	Measured	Sample
			$w_f$ (%)	$S_r$ (%)	$\rho_{dmax-f}$ (Mg/m <sup>3</sup> )	$w_f$ (%)	$\rho_{dmax-f}$ (Mg/m <sup>3</sup> )	$\rho_d$ (Mg/m <sup>3</sup> )
1	first		11	62		11.1	1.81	1.90
1'	first		11	62		11.0	1.82	1.90
2	second		11	62		11.3	1.82	1.91
2'	second	10	11	62		11.1	1.82	1.91
3	first		16	91		15.8	1.82	1.90
3'	first		16	91		15.7	1.82	1.90
4	second		16	91	1.82	15.7	1.82	1.91
5	first		11	62		10.8	1.80	2.10
5'	first		11	62		10.9	1.80	2.09
6	second		11	62		11.1	1.80	2.10
7	first	35	16	91		15.8	1.80	2.10
7'	first		16	91		15.9	1.80	2.10
8	second		16	91		15.8	1.80	2.10

Note:  $f_v$  represents the ratio of volumetric coarse grain content to the total volume of the sample (Wang 2018).  $w_f$  and  $\rho_{dmax-f}$  represent the water content and the maximum dry density of fine soils, respectively.  $\rho_d$  represents the dry density of fine/coarse soil mixture sample.  $S_r$  represents the degree of saturation of fine soil, which is also the degree of saturation of sample.

Table 3. Mechanical parameter from triaxial tests

Mechanical parameter	$f_v = 10\% (w_1=11\%)$				$f_v = 10\% (w_2=16\%)$			$f_v = 35\% (w_1=11\%)$			$f_v = 35\% (w_2=16\%)$		
	Test 1	Test 1'	Test 2	Test 2'	Test 3	Test 3'	Test 4	Test 5	Test 5'	Test 6	Test 7	Test 7'	Test 8
$q_{\max}$ (kPa)	397	427	230	284	132	135	115	459	451	490	242	230	225
$E_0$ (MPa)	27.5	31.4	20.1	22.5	5.1	5.7	4.5	40.4	40.4	41.9	9.9	9.9	9.8
$\nu$	0.23	0.23	0.24	0.24	0.34	0.33	0.33	0.23	0.23	0.22	0.34	0.32	0.32
$\psi$ (degree)	8.05	8.63	4.01	5.74	/	/	/	17.46	18.06	16.26	5.34	5.22	4.76