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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 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 ε_v plotted against the axial strain ε_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 ε_a . It appeared
196 from Fig. 7(a) that the deviator stress q of Test 1 (first approach) increased with the axial
197 strain ε_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 ε_v with axial strain ε_a . In Fig.
219 7(b) for all samples, the volumetric strain ε_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 ν and the dilatancy angle ψ . 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 ν and dilatancy angle ψ 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 ν 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 ν
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 (a₁) 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 (b₁), 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 (a₂)-(b₂)), 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 (a₁)-(b₁) 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 μm , $2 \mu\text{m}$ 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(a₂)-(b₂), the same uni-

289 modal microstructure with a population of micro-pores of 0.3 μm 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(a₁) - (b₁) and Fig. 13(a₁) - (b₁)), and a uni-modal porosity at $w_2 = 16\%$ on the wet
298 side (Fig. 12(a₂) - (b₂) and Fig. 13(a₂) - (b₂)). 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(b₁)), 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 (b₁)), 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(b₂)). 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(a₁) - (b₁)) and uni-modal for Test 7 and Test 8 at $w_2 = 16\%$ (Figs. 13(a₂) - (b₂)). 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(a₁) - (b₁))
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

ε_a	axial strain
ε_v	volumetric strain
ρ_d	dry density of sample
ρ_{dmax-f}	maximum dry density of fine soils
σ_3	confining pressure
ν	Poisson's ratio
ψ	dilatancy angle

427

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528

LIST OF TABLES

- Table 1. Suction and water content measured at different equilibration times for fine soils
Table 2. Soil properties of samples tested
Table 3. Mechanical parameter from triaxial tests

LIST OF FIGURES

- Fig. 1. Grain size distribution curves of fine soils (modified from Wang et al. 2018a)
Fig. 2. Grain size distribution curves of micro-ballast and ballast (modified from Wang et al. 2018a)
Fig. 3. Photographs of reconstituted fine soil and micro-ballast
Fig. 4. Plasticity of fine soils (modified from Wang et al. 2018a)
Fig. 5. Fine soil states defined in the two sample preparation approaches
Fig. 6. Photographs of samples compacted at $w_{\text{opt-f}} = 13.7\%$ and under various coarse grain contents
Fig. 7. Triaxial test results of samples at $f_v = 10\%$ on the dry side ($w_1 = 11\%$):
(a) stress-strain curves; (b) volumetric strain- axial strain curves
Fig. 8. Triaxial test results of samples at $f_v = 10\%$ on the wet side ($w_2 = 16\%$):
(a) stress-strain curves; (b) volumetric strain- axial strain curves
Fig. 9. Triaxial test results of samples at $f_v = 35\%$ on the dry side ($w_1 = 11\%$):
(a) stress-strain curves; (b) volumetric strain- axial strain curves
Fig. 10. Triaxial test results of samples at $f_v = 35\%$ on the wet side ($w_2 = 16\%$):
(a) stress-strain curves; (b) volumetric strain- axial strain curves
Fig. 11. Determination of Poisson's ratio and dilatancy angle
Fig. 12. Pore size distribution of fine soils for samples at $f_v = 10\%$: (a₁) - (b₁) on the dry side ($w_1 = 11\%$); (a₂) - (b₂) on the wet side ($w_2 = 16\%$)
Fig. 13. Pore size distribution of fine soils for samples at $f_v = 35\%$: (a₁) - (b₁) on the dry side ($w_1 = 11\%$); (a₂) - (b₂) on the wet side ($w_2 = 16\%$)
Fig. 14. Comparison of pore size distribution of fine soils for samples at $f_v = 10\%$ and $f_v = 35\%$

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 (%)	ρ_{dmax-f} (Mg/m ³)	w_f (%)	ρ_{dmax-f} (Mg/m ³)	ρ_d (Mg/m ³)
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 ρ_{dmax-f} represent the water content and the maximum dry density of fine soils, respectively. ρ_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
ν	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
ψ (degree)	8.05	8.63	4.01	5.74	/	/	/	17.46	18.06	16.26	5.34	5.22	4.76