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## Effects of water and fines contents on the resilient modulus of the interlayer soil of railway substructure

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35 **Abstract**

36 This paper deals with the resilient behavior of the interlayer soil which is created mainly by the  
37 interpenetration of ballast and sub-grade soils. The interlayer soil studied was taken from a site in  
38 the South-East of France. Large-scale cyclic triaxial tests were carried out at three water contents  
39 ( $w = 4, 6$  and  $12\%$ ) and three fines contents corresponding to  $5\%$  sub-grade added to the natural  
40 interlayer soil,  $10\%$  sub-grade added to the natural interlayer soil and  $10\%$  fine particles ( $< 80$   
41  $\mu\text{m}$ ) removed from the natural interlayer soil. Soil specimens underwent various deviator stresses,  
42 and for each deviator stress a large number of cycles were applied. The effects of deviator stress,  
43 number of cycles, water content and fines content on the resilient modulus ( $M_r$ ) were analyzed. It  
44 appears that the effects of water content and fines content must be analyzed in a global fashion  
45 because the two effects are closely linked. Under unsaturated conditions, the soil containing high  
46 fines content has higher resilient modulus due to the contribution of suction. When the soil  
47 approaches the saturated state, it loses its mechanical performance with a sharp decrease in  
48 resilient modulus.

49 *Keywords:* railway sub-structure; interlayer soil; resilient modulus; fines content; water content;  
50 large-scale cyclic triaxial test.

51

## 52 **Introduction**

53 The soils in the sub-structures of highway and railway are subjected to a huge number of traffic  
54 loading cycles. In this context, the resilient modulus of sub-structure soils is an important  
55 parameter to be considered when designing new tracks or when maintaining under-operation  
56 tracks. Indeed, several authors [1, 4, and 28] reported that the resilient modulus of sub-grade can  
57 strongly influence the mechanical behavior of sub-structure.

58 For the French ancient railway tracks constructed in the 1880s, as ballast was placed  
59 directly on the sub-grade during the construction without any separation layers, an interlayer was  
60 naturally created over time mainly by the interpenetration of ballast and sub-soil under the traffic  
61 effect [5-7, 32]. This interlayer has been kept as part of the sub-structure considering its high  
62 mechanical performance related to its high unit mass [33]. As the interlayer is a “component” of  
63 the sub-structure overlying the sub-grade, its mechanical behavior appears to be of primary  
64 importance for the overall behavior of sub-structure even the overall track structure. However,  
65 because this material has been formed naturally, it can present large variability in terms of fines  
66 natures and fines contents. Moreover, under the effect of climatic conditions, soil water content  
67 changes also constantly. These changes in fines content, fines nature and water content can  
68 greatly affect soil mechanical behavior such as soil resilient modulus.

69 The notion of resilient behavior appeared for the first time in the middle of the 20<sup>th</sup>  
70 century [16, 17]. In the railway context, the resilient modulus ( $M_r$ ) is defined as the secant slope  
71 of the curve of deviator stress versus axial strain obtained from cyclic triaxial tests [21, 26-28, 30,  
72 and 37]. Previous studies showed that there are several factors that affect the resilient modulus of  
73 unbound granular materials, in particular the stress level [14, 22, 24, 26, and 30]. The increase in  
74 moisture content appears to decrease the resilient modulus [10, 11, and 14]. For the effect of

75 loading cycles, a large disagreement exists in terms of number of cycles required to reach the  
76 stabilization of resilient modulus [23, 24, 30, 35, 36]. As far as the effect of fines content is  
77 concerned, there is no conclusive observation as mentioned by Lekarp et al. [24]. Thom and  
78 Brown [31] and Kamal et al. [20] reported that the resilient modulus generally decreases when  
79 the fines content increases. However, Jorenby and Hicks [19] observed that the stiffness of  
80 crushed aggregate has an initially increase trend followed by a considerable reduction when  
81 clayey fines content increased.

82 All these factors (moisture content, fines content, number of cycles) influence the resilient  
83 response of materials. However, to the authors' knowledge, their combined effect has rarely  
84 investigated especially for the interlayer soil. In the present work, large-scale cyclic triaxial tests  
85 were carried out to study the variations of  $M_r$  of an interlayer soil under the combined effects of  
86 stress level, water content, fines content and cyclic loadings.

## 87 **Materials and methods**

88 The studied interlayer soil was taken from S nissiat, near Lyon, France. The grain size  
89 distribution curves of the natural interlayer soil ( $ITL_0$ ) and the sub-grade soil (SG) are presented  
90 in Fig. 1. It can be observed that the interlayer soil has a large fines content (16% of particles are  
91 smaller than 80  $\mu\text{m}$ ), and its grain size distribution curve is well graded from ballast size (60 mm)  
92 to clay size ( $< 2 \mu\text{m}$ ). Its physical properties (density, plasticity index, blue methylene value and  
93 proctor curve) of this material were reported by Trinh et al. [33, 34]. For the SG, almost all soil  
94 particles are smaller than 80  $\mu\text{m}$ .

95 In order to study the influence of fines content, the fines content of the soil was varied by  
96 either removing fine particles smaller than 80  $\mu\text{m}$  from the interlayer soil (-10% for  $ITL_{-10}$ ) or  
97 adding sub-grade soil into the interlayer soil (+5% for  $ITL_5$  and +10% for  $ITL_{10}$ ). The percentages

98 refer to the ratio of dry mass of fine particles to dry mass of interlayer soil. The removal of fine  
99 particles for the preparation of *ITL<sub>10</sub>* was done by sieving. The grain size distribution curves of  
100 *ITL<sub>10</sub>*, *ITL<sub>5</sub>* and *ITL<sub>10</sub>* are also shown in Fig. 1.

101 For the specimen preparation, water were first added and mixed with the material using a  
102 large mixer to reach the target water content. After mixing, the wet materials were stored in  
103 hermetic containers for at least 24 h for moisture homogenization. Compaction was performed in  
104 6 layers of 0.1 m thick each using a vibratory hammer to a dry unit mass of 2.01 Mg/m<sup>3</sup>. This is  
105 the maximum dry unit mass which can be reached in the adopted conditions without breaking  
106 ballast particles.

107 Because large particles were involved, a large-scale triaxial apparatus developed by Dupla  
108 et al. [8] was used, enabling specimens of 300 mm in diameter and 600 mm in height to be tested.  
109 This apparatus can apply large number of loading cycles (up to several millions) at a frequency  
110 up to several tens of Hertz.

111 The program of tests is presented in Table 1. All the four soils were tested at three water  
112 contents ( $w = 4\%$ ; 6% and 12%) corresponding to three initial degrees of saturation ( $S_{ri} = 32\%$ ;  
113 49% and 100%), except *ITL<sub>5</sub>* on which only one test at a water content of  $w = 6\%$  was conducted  
114 owing to lack of material. The tests are named according to the material (*ITL<sub>10</sub>*, *ITL<sub>0</sub>*, *ITL<sub>5</sub>*, *ITL<sub>10</sub>*)  
115 and water content. For instance, *ITL<sub>0</sub>w4* corresponds to the test on *ITL<sub>0</sub>* at 4% water content. To  
116 overcome the problem related to the limited material quantity, the multi-step loading procedure  
117 proposed by Gidel et al. [12] was adopted. This procedure enables several deviator stress levels to  
118 be applied before the soil specimen reaches the failure state, thereby reducing the number of tests  
119 on one hand and avoiding the effect of variability of soil specimens on the other hand.

120 The cyclic triaxial tests were performed under a constant confining pressure  $\sigma_3 = 30$  kPa.  
121 This value was chosen by referring to the wheel load generated by train [2], the depth of the  
122 interlayer (from 250 mm to 600 mm), the Poisson's ratio (0.3 - 0.4 as proposed by Selig and  
123 Waters [28]). The vertical stress at the top of interlayer was found to be 40 to 90 kPa. These  
124 values correspond to the Indian railways as reported by Jain and Keshav [18] and American  
125 railways as reported by Selig and Waters [28] and Yang et al. [39]. In other countries where  
126 heavier wagons are used, the wheel load may reach 30 tons per axle [2], leading to a vertical  
127 stress of 120 to 140 kPa on the interlayer [13, 18, 25]. In this study, a maximum deviator stress of  
128 200 kPa was applied. All the tests were performed under drained condition; the valves were open  
129 (under unsaturated condition) or connected to a water back pressure source (under saturated  
130 condition). During the saturated triaxial test, the back pressure was kept constant and pore water  
131 can drain freely. For the loading frequency, a value of 5 Hz was chosen because this is the  
132 dominant one among a number of frequencies generated in the French ancient sub-structures at a  
133 train speed of 100 km/h [29]. During the tests, the deviator stress was increased in steps from 0 to  
134 various target values; in each step, 30 000 cycles were applied and the variations of axial strain  
135 were recorded.

## 136 **Results**

137 Fig. 2 presents typical curves of deviator stress versus axial strain for the first cycles in test  
138 *ITL<sub>5w6</sub>*. It also shows the definition of permanent axial strain ( $\epsilon_p$ ), the resilient axial strain ( $\epsilon_r$ )  
139 through the first cycle. It can be observed that the minimum deviator stress did not totally reach  
140 zero for all cycles. This was probably due to the high loading/unloading speed (frequency of 5  
141 Hz) that caused a delay between the target signal and the real signal. However, it is believed that

142 this problem does not affect the resilient modulus ( $M_r$ ) that corresponds to the secant slope of  
143 curves (see Fig. 2).

144 Fig. 3 plots the deviator stress versus the axial strain for the moments where the values of  $\Delta q_{max}$   
145 were increased: during the first 8 cycles ( $N = 8$ ) under  $\Delta q_{max} = 45$  kPa (Fig. 3a), from  $\Delta q_{max} = 45$   
146 kPa ( $N = 30\,000$ ) to  $\Delta q_{max} = 90$  kPa ( $N = 30\,001 - 30\,0004$ ) (Fig. 3b), from  $\Delta q_{max} = 90$  kPa ( $N =$   
147  $60\,000$ ) to  $\Delta q_{max} = 145$  kPa ( $N = 60\,001 - 60\,0004$ ) (Fig. 3c) and from  $\Delta q_{max} = 145$  kPa ( $N =$   
148  $90\,000$ ) to  $\Delta q_{max} = 20$  kPa ( $N = 90\,001 - 90\,0004$ ) (Fig. 3d). It can be observed that when a new  
149 deviator stress was applied, the axial strain increased accordingly. During the very first cycles  
150 under each stress level, the loading and unloading paths did not form close cycles, suggesting that  
151 significant permanent axial strain developed. In this case, the resilient modulus was determined  
152 based on the unloading path of a cycle and the loading path of the next cycle. The hysteresis loop  
153 was large in the first cycles, and with the increase of number of cycles, this hysteresis became  
154 less and less significant. At large number of cycles by the end of each loading level, the material  
155 behaved almost in a purely elastic fashion. Werkmeister et al. [38] reported that the change in the  
156 loop shape provides information about the different deformation mechanisms. In the beginning,  
157 there was probably particles rotation and rearrangement producing the plastic strain. Over time,  
158 these particles movements became limited and a purely resilient state is reached where strain is  
159 due to the deformation at the contacts of particles. Note that the shape of loading/unloading loops  
160 is related to the slope adopted for the determination of the resilient modulus. When two paths  
161 formed a close cycle, the straight line between the lowest and highest point of the  
162 loading/unloading cycle was used in the determination.

163 Fig. 4 depicts the evolution of resilient strain with number of cycles for test *ITL<sub>2w12</sub>*.  
164 When the deviator stress increased, the resilient strain increased sharply during the first cycles of



165 each stress level, and decreased afterwards to reach stabilization. The resilient strain was larger  
166 under higher deviator stress.

167 Fig. 5 depicts the variations of  $M_r$  with the number of cycles ( $N$ ) at three water contents  
168 and various deviators stress levels for  $ITL_{10}$ . In the case of  $ITL_{10w4}$  (Fig. 5a) at  $\Delta q_{max} = 23$  kPa,  
169 the data of resilient modulus shows some scatter, but in general an increase trend can be  
170 identified. Because of the data scatter, it is difficult to determine the number of cycles at which  
171 the stabilization of resilient modulus started. The values in other stress levels are more or less  
172 constant around 250 MPa. For  $ITL_{10w6}$  (Fig. 5b), the resilient modulus for all stress levels are  
173 found to increase significantly in the beginning and then stabilize after around 15 000 cycles.  
174 When  $\Delta q_{max}$  was increased from 45 kPa to 90 kPa, the resilient modulus rose up sharply. By  
175 contrast, an opposite trend was observed when  $\Delta q_{max}$  was increased from 90 to 140 kPa. It can be  
176 seen from Fig. 5c that for each deviator stress level, the resilient modulus decreased during the  
177 first cycles. For instance, it decreased from 168 MPa to 144 MPa from cycle 1 to cycle 7.  
178 However, this decreasing trend came very quickly to its end and was replaced by an increasing  
179 one. Afterwards, the increase rate slowed down and the resilient modulus value tended to  
180 stabilize after about 5000 loading cycles. Referring to Fig. 4, the significant variations of resilient  
181 modulus in Fig. 5 correspond to the phase characterized by quick development of resilient axial  
182 strain just after the change of stress level, and the stabilization states of resilient modulus  
183 corresponds to the stabilization of resilient axial strain.

184 These observations are confirmed in the case of  $ITL_{5w6}$  (see Fig. 6). For all stress levels, the  
185 resilient modulus increased with the number of cycles during the first cycles. At  $\Delta q_{max} = 45$  kPa  
186 about 10 000 cycles were needed for the resilient modulus to become stable while at  $\Delta q_{max} = 140$   
187 kPa and 200 kPa, about 5000 cycles were needed. The variation range of  $M_r$  at all stress levels is

188 about  $\pm 10$  MPa. On the whole, the effect of deviator stress is not as clear as in the case of  
189 *ITL<sub>10</sub>w6*.

190 The results of *ITL<sub>0</sub>* are presented in Fig. 7. The variation of  $M_r$  with  $N$  is more pronounced in the  
191 case of *ITL<sub>0</sub>w12* (Fig. 7c) than in the cases of *ITL<sub>0</sub>w4* (Fig. 7a) and *ITL<sub>0</sub>w6* (Fig. 7b). After the  
192 first variations when the deviator stress  $\Delta q_{max}$  changed, the resilient modulus increased with the  
193 number of cycles in the case of *ITL<sub>0</sub>w12*, while the changes in the two other cases are not clear.

194 As regards *ITL<sub>-10</sub>*, the results with three different water contents are presented in Fig. 8. In the  
195 two cases of  $w = 4\%$  and  $12\%$ , the resilient modulus did not vary much for the deviator stress up  
196 to 90 kPa, suggesting an insignificant influence of the number of cycles. Also, the influence of  
197  $\Delta q_{max}$  is insignificant because albeit the variation of  $\Delta q_{max}$ , the resilient modulus remained at a  
198 steady value: about 230 MPa for *ITL<sub>-10</sub>w12* and 250 MPa for *ITL<sub>-10</sub>w4*. In the case of  $w = 6\%$   
199 (Fig. 8b), the variation is clearer as the results show a slight increasing trend of  $M_r$  with the  
200 number of cycles and  $\Delta q_{max}$ . At the stress level of 140 kPa, there was a sharp decrease of  $M_r$ ,  
201 regardless of the water content: for the three tests, when  $\Delta q_{max}$  was increased from 90 kPa to 140  
202 kPa, a reduction of  $M_r$  of about 50 kPa was produced. Afterwards, the variations of resilient  
203 modulus with the number of cycles became much more pronounced than in the cases of other  
204 deviator stress levels.

## 205 **Discussions**

206 From the test results, it was observed that after a few scattered results at the beginning of each  
207 stress level, the resilient modulus became stable with the number of cycles. However, the  
208 variations were different for different soils and different water contents. The variations were clear  
209 in the case of *ITL<sub>10</sub>* (Fig. 5b and c), insignificant in the first part of test *ITL<sub>0</sub>w4* (Fig. 7a) and *ITL*.

210  $_{10}w4$  (Fig. 8a). The stabilization value was reached right after the first cycles in test  $ITL_{0}w4$  (see  
211 Fig. 7a) and after 15 000 cycles in test  $ITL_{10}w6$  (see Fig. 5b). Therefore, it can be stated that the  
212 number of cycles needed for  $M_r$  to reach stabilization depends on the stress level, water content,  
213 and fines content. This can explain the disagreement found in literature regarding the number of  
214 cycles required to attain a stable resilient state: Stewart [30] studied the ballast behavior and  
215 reported a stabilization after 1000 cycles while Hicks and Monismith [14] and Allen and  
216 Thompson [3] (cited by Lekarp et al. [24] and Lackenby [23]) observed that 50 – 100 cycles are  
217 needed for the stabilization for granular materials.

218 The variations of resilient modulus during the scattered phase at the beginning of each  $\Delta q_{max}$  were  
219 observed in all tests. This phase corresponds to the stage where the permanent axial strain  
220 developed quickly and the loading/unloading path did not form a close cycle in the deviator stress  
221 – axial strain plane. This can be explained as follows: when  $\Delta q_{max}$  was increased, the soil  
222 behavior became elasto-plastic; thus irreversible strain was produced. However, this phenomenon  
223 occurred during the first loading. Afterwards, the cyclic loading led to a progressive stabilization  
224 of the particles arrangement, thereby a negligible plastic strain.

225 For a better analysis on the effects of deviator stress and water content, the end-level resilient  
226 modulus values (after 30 000 cycles for each deviator stress level) are plotted versus deviator  
227 stress in Fig. 9. For  $ITL_{10}$  (Fig. 9a), the results at 4% and 12 % water contents present a slight  
228 decrease of resilient modulus when the deviator stress was increased from 23 to 102 kPa. On the  
229 contrary, in the case of 6% water content, the resilient modulus increased and then reached  
230 stabilization. The values of 4% and 6% water contents fall in the same range, around 250 MPa  
231 and clearly higher than the values of 12% water content. For  $ITL_0$  (Fig. 9b), at 4% and 6% water  
232 content, the resilient modulus increased with the deviator stress and the values of 4% are higher

233 than those of 6%. The values of  $ITL_0$  in near saturated state ( $w = 12\%$ ) are, as opposed to the case  
234 of  $ITL_{10}$ , higher than those of 4% water content. In the case of  $ITL_{-10}$  (Fig. 9c), the curves have  
235 almost the same shape: a stage of slight variations up to 90 kPa of deviator stress followed by a  
236 stage of decrease, the decrease being more pronounced in the case of  $ITL_{-10w12}$ .

237 In terms of water content effect, the value of  $ITL_{-10}$  at 4% water content is the highest; the values  
238 of 12% water content are lower than those of 4% water content but higher than those of 6% water  
239 content. The relative positions of these curves show that the water content effect is not the same  
240 for the three materials. It appears that the increase of water content brings a negative effect to the  
241 resilient modulus of the soil that has the highest fines content ( $ITL_{10}$ ). However, for  $ITL_0$  and  $ITL_{-10}$ ,  
242 the resilient modulus decreased when water content changed from 4% to 6% but increased  
243 when water content was increased to 12%. Note that only a decreasing trend of resilient modulus  
244 with growing saturation level for granular material was observed by Lekarp [24]. More studies  
245 are required to clarify this issue.

246 For  $ITL_{-10}$ , a deviator stress of 90 kPa appears to be the critical value for the variations of  
247 resilient modulus: all tests showed a decrease of resilient modulus at this stress level, suggesting  
248 a significant change in soil behavior. As mentioned previously, after a certain number of cycles,  
249 the resilient behavior was mainly governed by the contacts of soil particles. When the imposed  
250 deviator stress increased, the stress applied at the inter-particles contact exceeds its limit and  
251 particle breakage may occur. As a result, a sharp decrease of  $M_r$  is produced. This could be the  
252 case for  $ITL_{-10}$  that has the lowest fines content. For  $ITL_0$  and  $ITL_{10}$ , this phenomenon of particle  
253 breakage was probably attenuated, leading to much smaller decrease of  $M_r$ .

254 As far as the effect of water content is concerned, the results show that the relative  
255 positions of the curves of three different water contents are not the same for the three materials.  
256 This suggests that the soil composition can strongly influence the material resilient modulus. Fig.  
257 10 presents the results according to the water content: 4%; 6% and 12% in Figs. a, b and c,  
258 respectively. The effect of fines content can be observed clearly. In the case of  $w = 4\%$ , the  
259 results of  $ITL_{-10}$  and  $ITL_{10}$  are almost identical for the deviator stress up to 100 kPa. But much  
260 lower values are observed for  $ITL_0$  for the deviator stress up to 140 kPa. Beyond 140 kPa deviator  
261 stress, the values become almost the same for  $ITL_{-10}$  and  $ITL_0$ . At 6% water content, the resilient  
262 modulus of  $ITL_0$  is also the smallest, showing that when decreasing the fines content (from  $ITL_{10}$   
263 to  $ITL_0$ ), a reduction of resilient modulus is produced. However, when the fines content is  
264 decreased to a level as low as  $ITL_{-10}$ , the resilient modulus starts to increase. Under the near  
265 saturation conditions ( $w = 12\%$  in Fig. 10c), it is observed that the greater the fines content, the  
266 lower the resilient modulus.

267 Fig. 11 plots the end stage resilient modulus at three stress levels with the variation of  
268 water content and fines content. Despite of the scatter, it can be generally observed a clear trend  
269 of  $M_r$  at all water content. It slightly decreases when the fine content added increases from -10% to  
270 0%. After that, it can be observed a significant increase of  $M_r$  when the fine content added passes  
271 to 10%. Adding more fine particles, in one hand, limited the contact between big particles contact  
272 (ballast), but in other hand, increase the suction, as the gravimetric water content was kept  
273 constant.

274 To identify the mechanisms of these phenomena, it appears necessary to consider the combined  
275 effects of the fines content and the water content which is linked to the soil suction. It is well  
276 known that for unsaturated soils, suction contributes to the soils shear strength, especially for the

277 fine-grained soils. This explains why fine particles show a positive effect on the resilient modulus  
278 under unsaturated conditions, but a negative effect under saturated conditions. It can be observed  
279 in the case of  $\Delta q_{max} = 45$  kPa (Fig. 11a), for the case of 12% of water content, there was no more  
280 suction effect, and the resilient modulus decrease with the increase of fine content. This implies  
281 that in unsaturated conditions, due to the suction effect the interlayer soil containing high fines  
282 content has a better mechanical performance, while in near saturation conditions, higher fines  
283 contents leads to a significant degradation of mechanical performance. This is in agreement with  
284 the observations of Huang et al. [15], Ebrahimi [9] and Duong et al. [7]. From a practical point of  
285 view, these findings are important for the maintenance of railway tracks. If the soil containing  
286 high fines content can satisfy the requirements in terms of resilient modulus under unsaturated  
287 conditions, measures must be taken to protect it from water infiltration. Very often, it is a good  
288 drainage system that should be set up for this purpose.

## 289 **Conclusions**

290 The resilient behavior of an interlayer soil taken in a railway sub-structure in France was studied  
291 in the laboratory. The effects of deviator stress level, number of cycles, water content and fine  
292 content were investigated by performing large-scale cyclic triaxial tests. Four fines contents and 3  
293 water contents were considered.

294 At each deviator stress level, after the first scattered results due to the plastic behavior of  
295 soil, the resilient modulus tended to stabilize with the number of cycles. It was found that the  
296 number of cycles needed to reach stabilization depends on the material nature, water content and  
297 stress level.

298 The effects of water content and of fines content are linked, and it appeared impossible to  
299 distinguish the two effects. Indeed, in unsaturated conditions, due to the suction effect, the soil

300 having high fines content showed higher resilient modulus. On the contrary, when the soil  
301 approached the saturated conditions, the fine particles provided a negative effect. This suggests  
302 that drainage measures must be taken to protect the interlayer soil when its mechanical  
303 performance appears satisfactory under unsaturated conditions but unsatisfactory under saturated  
304 conditions.

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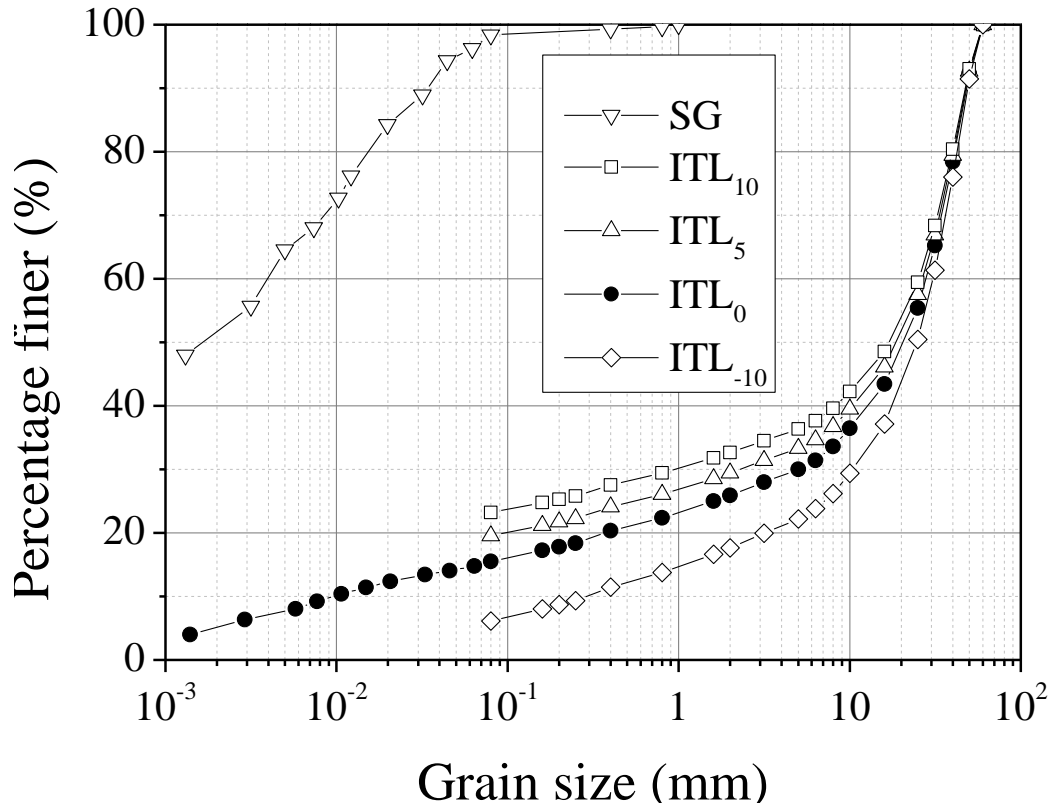
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433 **Table 1: Test program**

Soil	Water content - $w$ (%)		
	4 %	6 %	12 %
ITL <sub>10</sub>	ITL <sub>10</sub> w4	ITL <sub>10</sub> w6	ITL <sub>10</sub> w12
ITL <sub>5</sub>	-	ITL <sub>5</sub> w6	-
ITL <sub>0</sub>	ITL <sub>0</sub> w4	ITL <sub>0</sub> w6	ITL <sub>0</sub> w12
ITL <sub>-10</sub>	ITL <sub>-10</sub> w4	ITL <sub>-10</sub> w6	ITL <sub>-10</sub> w12

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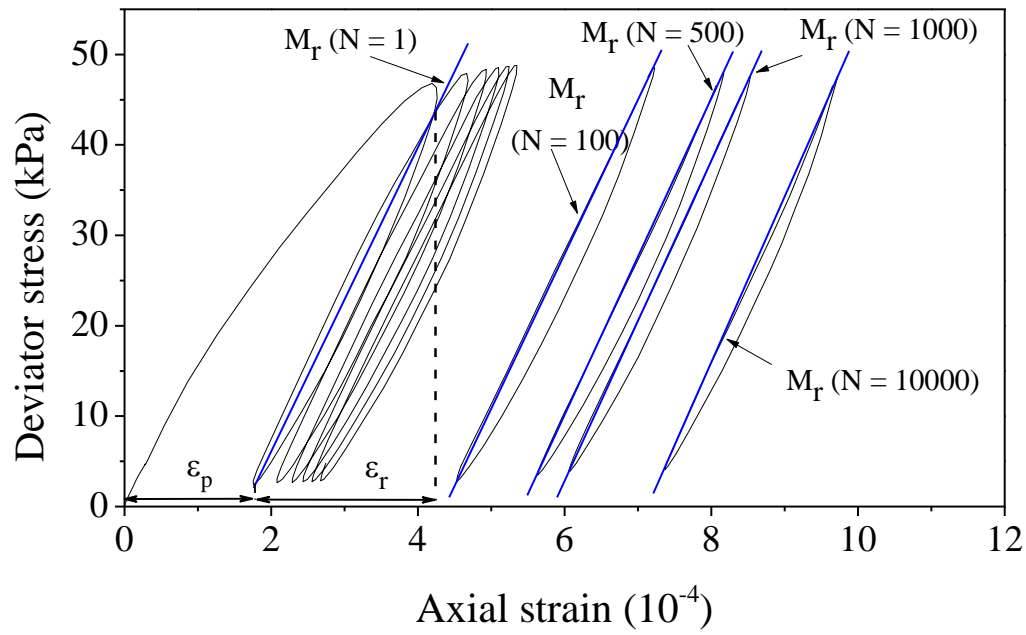


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439 **Fig. 1: Grain size distribution of the studied materials**

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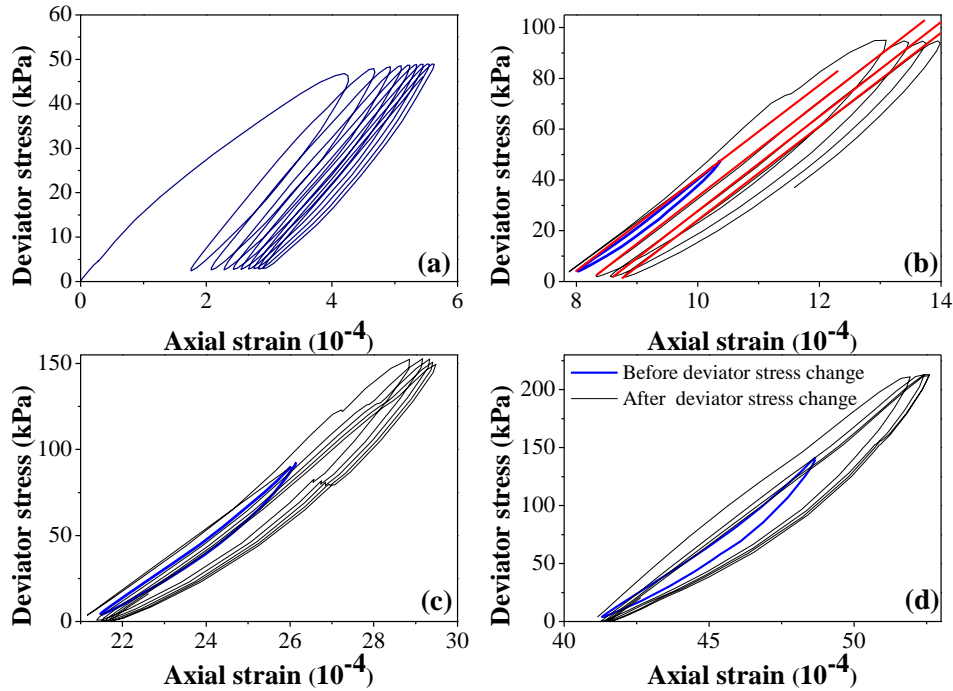
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443 **Fig. 2: Deviator stress versus axial strain for test ITL<sub>5</sub>w6 - Determination of resilient**  
444 **modulus**

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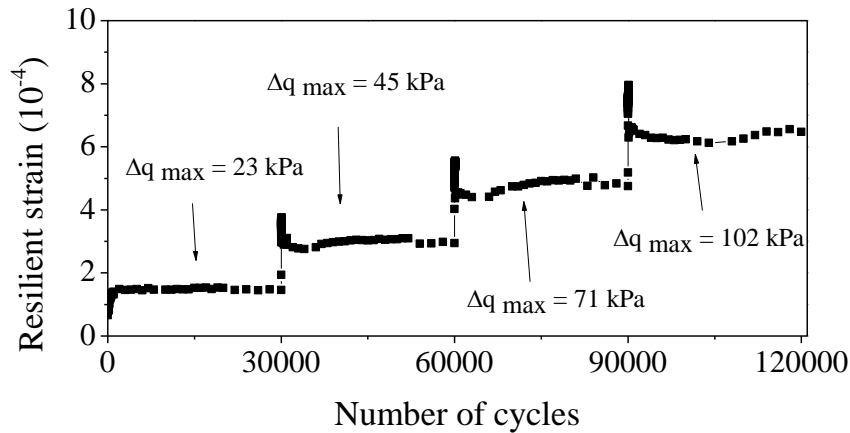




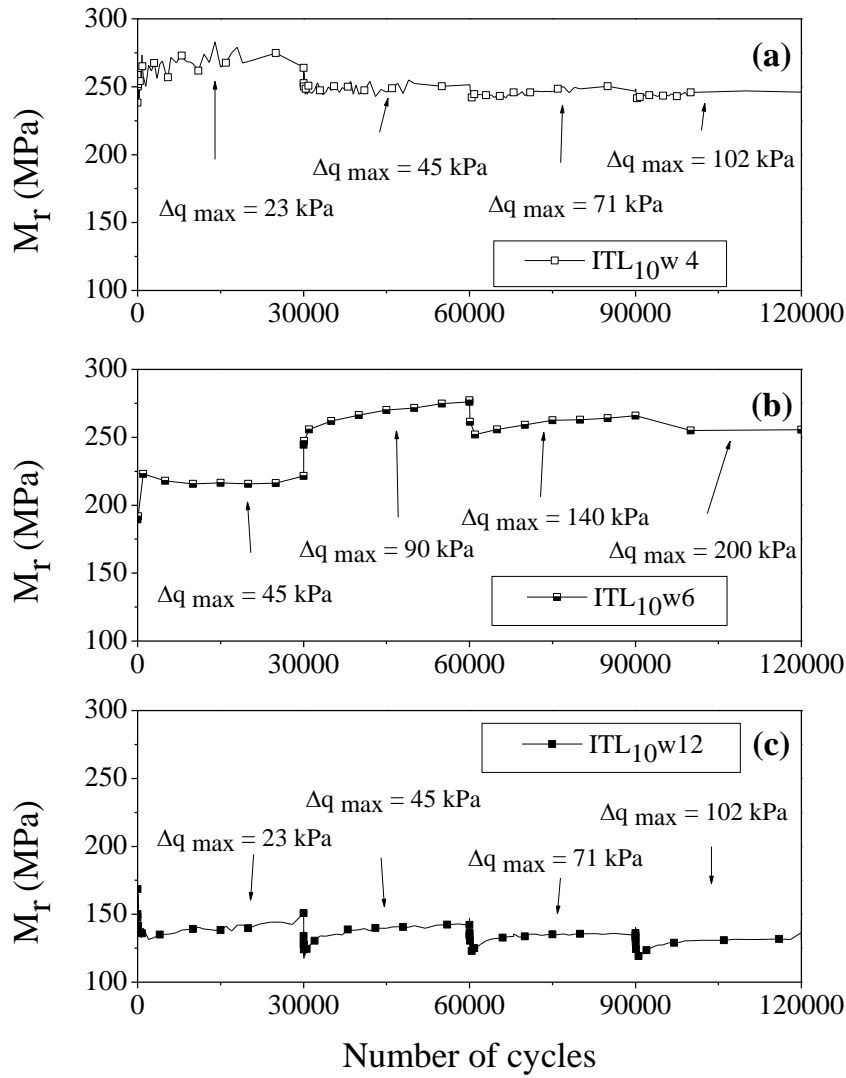
447  
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 449 **from  $\Delta q_{max} = 45$  kPa (N = 30 000) to  $\Delta q_{max} = 90$  kPa (N = 30 001 - 30 0004); c) from  $\Delta q_{max} =$**   
 450  **$90$  kPa (N = 60 000) to  $\Delta q_{max} = 145$  kPa (N = 60 001 - 60 0004); d) from  $\Delta q_{max} = 145$  kPa (N**  
 451 **= 90 000) to  $\Delta q_{max} = 20$  kPa (N = 90 001 - 90 0004)**

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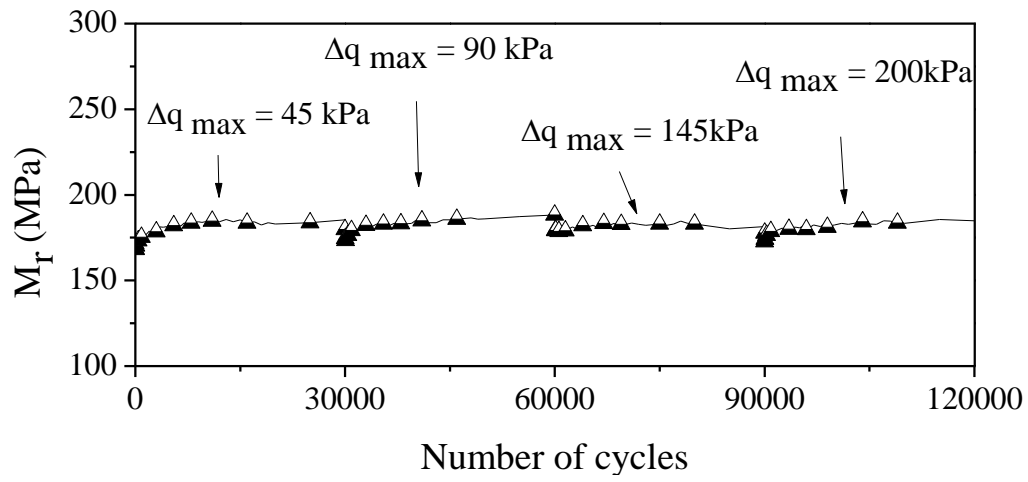


454  
 455 **Fig. 4: Resilient strain versus number of cycles in test ITL<sub>10</sub>w12**



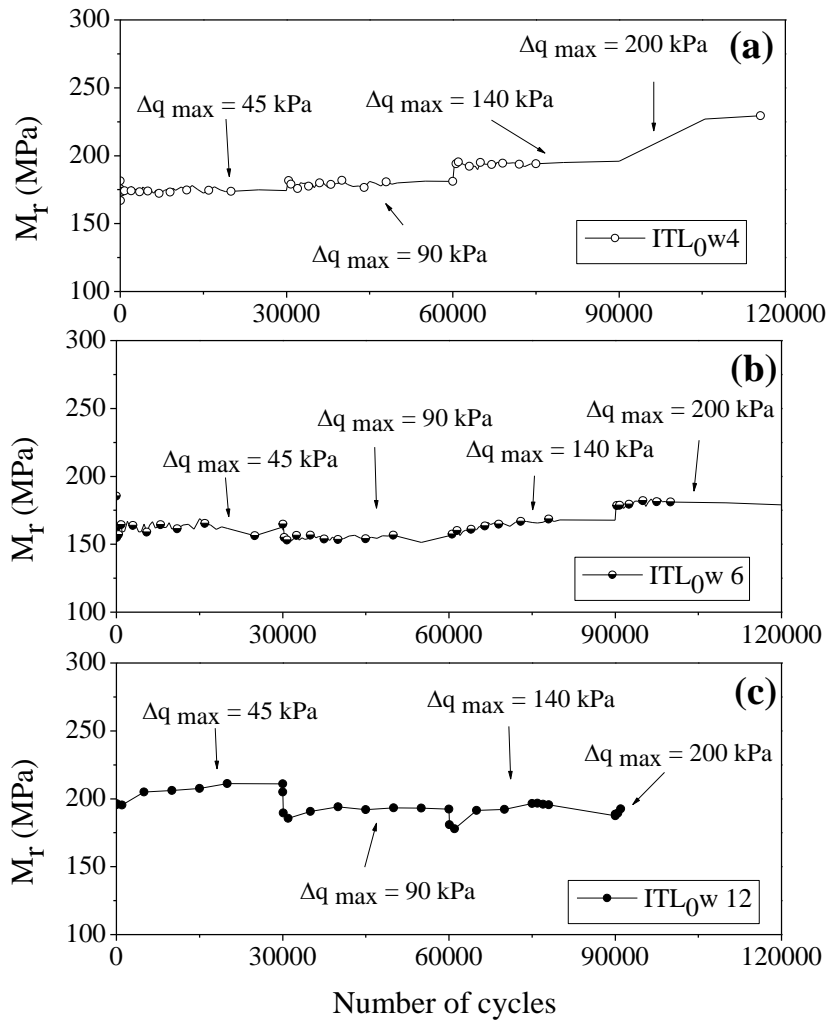
458 **Fig. 5: Resilient modulus versus number of cycles for  $ITL_{10}$ . a)  $w = 4\%$ ; b)  $w = 6\%$ ; c)  $w =$**   
 459 **12%**  
 460

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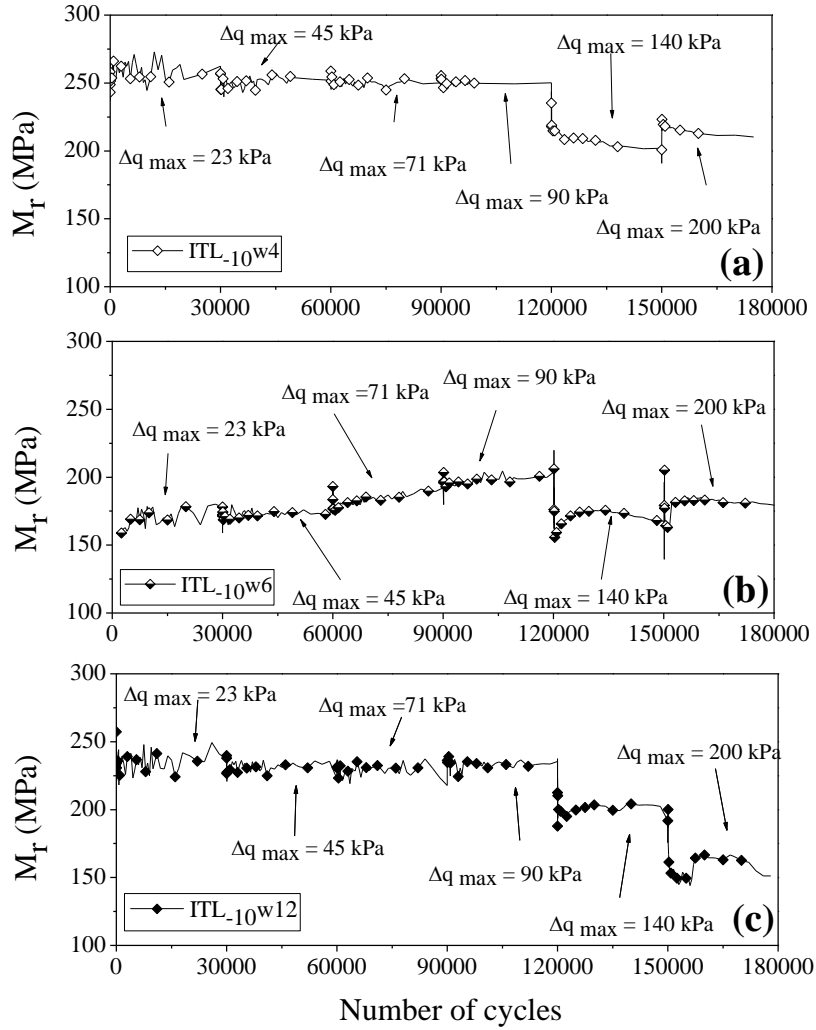
463 **Fig. 6: Resilient modulus versus number of cycles for ITL<sub>5</sub>w6**



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465 **Fig. 7: Resilient modulus versus number of cycles for  $ITL_0$ . a)  $w = 4\%$ ; b)  $w = 6\%$ ; c)  $w =$**   
 466  **$12\%$**

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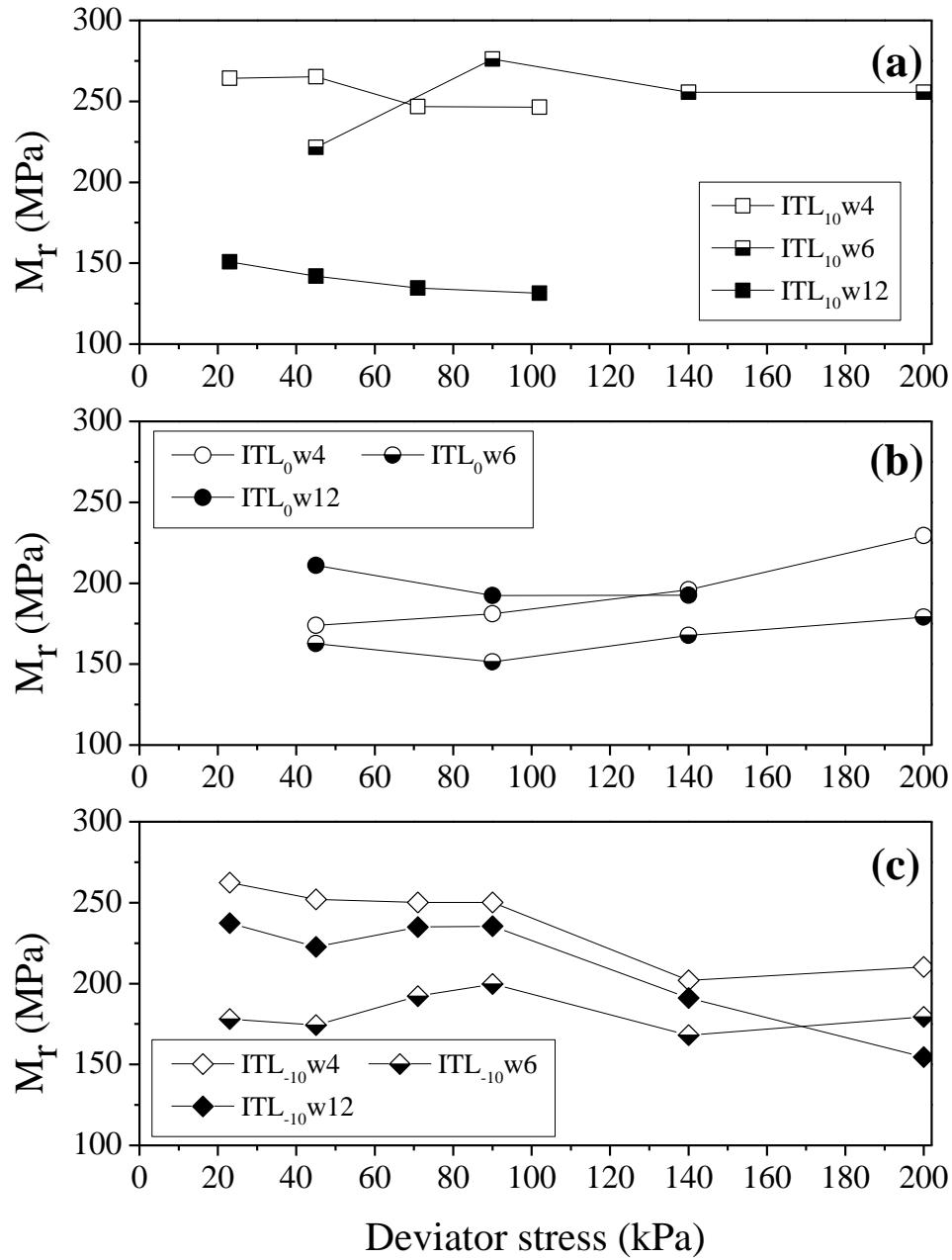


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469 **Fig. 8: Resilient modulus versus number of cycles for ITL-10. a)  $w = 4\%$ ; b)  $w = 6\%$ ; c)  $w =$**   
 470 **12%**

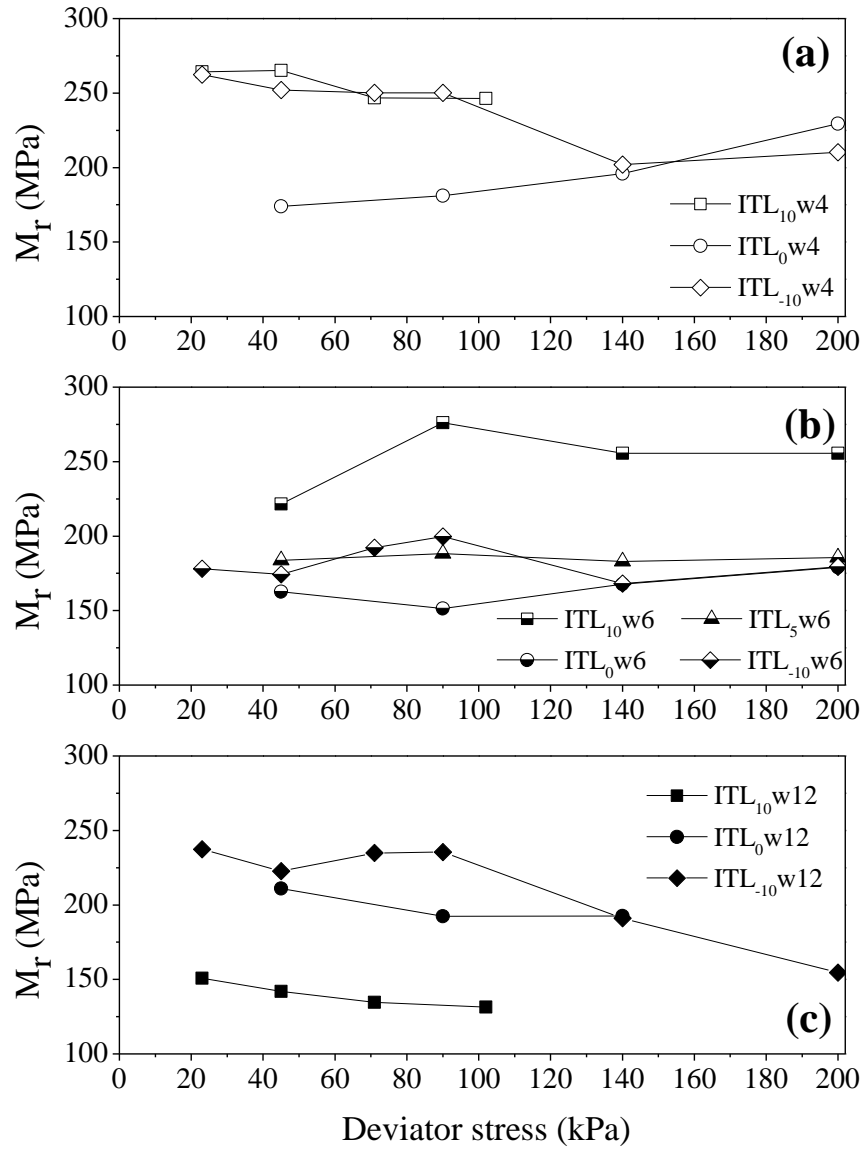
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474 **Fig. 9: End-stage resilient modulus versus deviator stress - Effect of water content. a)  $IITL_{10}$ ;**  
 475 **b)  $IITL_0$ ; c)  $IITL_{-10}$**

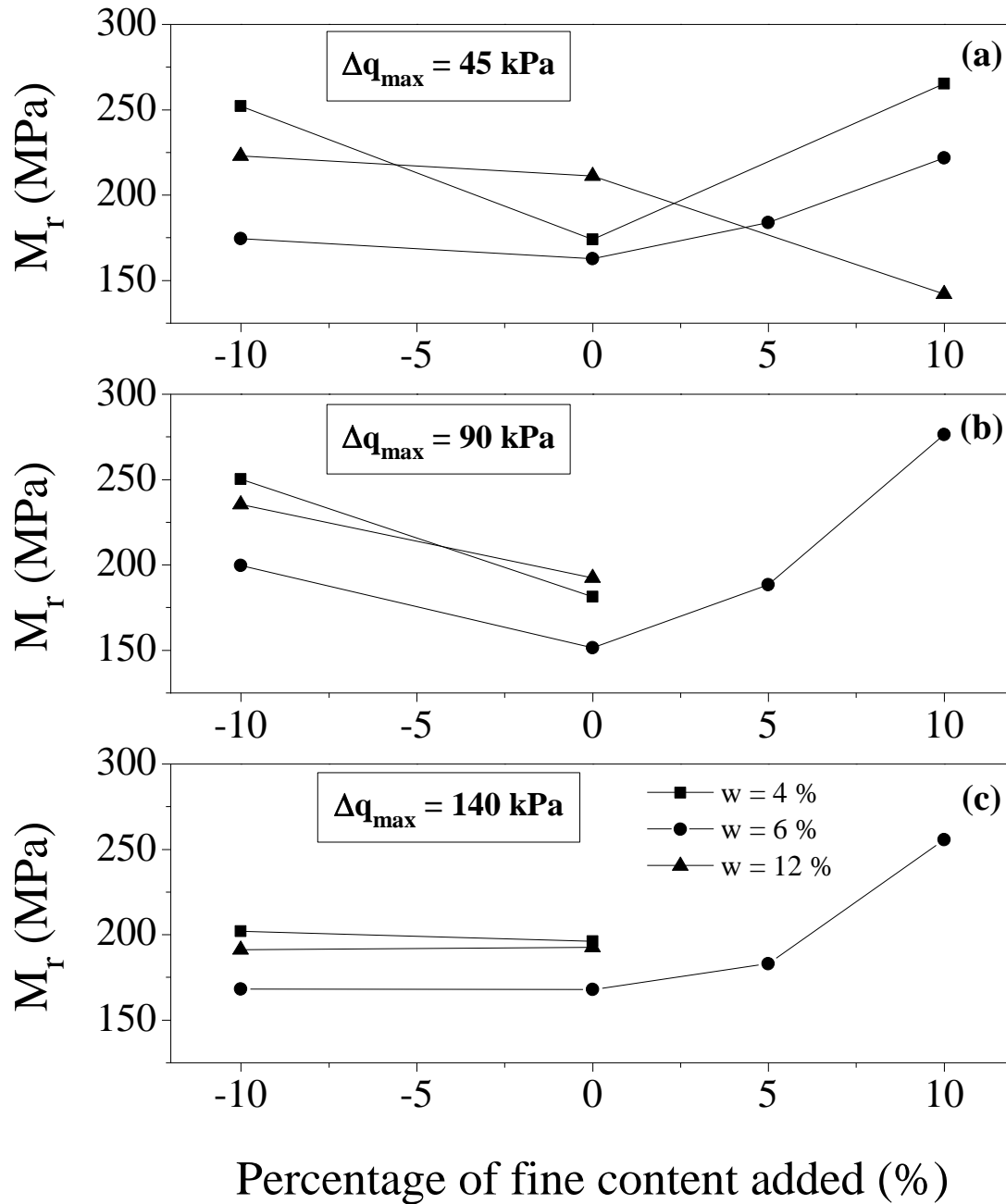


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477 **Fig. 10: End-stage resilient modulus versus deviator stress - Effect of fines content. a)  $w =$**   
 478 **4%; b)  $w = 6\%$  and c)  $w = 12\%$**

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 482 **Figure 11: Resilient modulus in function of water content at different fine contents; a) at  $\Delta q_{max} = 45$  kPa; b) at**  
 483  **$\Delta q_{max} = 90$  kPa and c) at  $\Delta q_{max} = 140$  kPa**