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Abstract

In the French conventional railway track, an interlayer was created naturally through the interpenetration of ballast and subgrade under the effect of long-term train loading. Field investigation showed that the proportion of ballast grains decreased over depth in the interlayer. Moreover, the water content of interlayer soils varies depending on the weather conditions, which can strongly affect the mechanical behavior of interlayer soil. In this study, the effect of water content on the mechanical behavior of interlayer soils under various coarse grain contents was investigated by monotonic triaxial tests. Three water contents (w = 17.6%, 10.6%, and 7.0%), five volumetric coarse grain contents (f_v = 0%, 10%, 20%, 35%, and 45%) and three confining pressures (σ_3 = 30 kPa, 60 kPa and 120 kPa) were considered. Results showed that a decrease of w led to an increase of shear strength and soil stiffness due to the effect of suction, and to an increase of dilatancy due to the aggregation of fine soils. Moreover, the variations of maximum deviator stress $q_{\max}$, Young's modulus E_0, dilatancy angle ψ and friction angle φ with f_v followed a bi-linear pattern for the three σ_3 values, defining a characteristic volumetric coarse grain content $f_{v\text{-cha}}$ value for a given w value: $f_{v\text{-cha}} \approx$ 25%, 29% and 33% for w = 17.6%, 10.6% and 7.0%, respectively. The $f_{v\text{-cha}}$ corresponded to the transition from a structure dominated by fine soils to a structure dominated by coarse grains. The increase of $f_{v\text{-cha}}$ with the decrease of w could be attributed to the swelling and shrinkage of fines. While drying from optimum water content of fines $w_{opt\text{-}f}$ =13.7% to a lower w_f value, more coarse grains were needed to constitute the global skeleton due to the increase of the global volume of macro-pores resulted from the shrinkage of fine soils. By contrast, while wetting from $w_{opt\text{-}f}$ =13.7% to a higher w_f value, since the global volume of macro-pores decreased due to the swelling of fine soils, less coarse grains were required to constitute the global skeleton.

Keywords: fabric/structure of soils; partial saturation; laboratory tests; compaction; shear strength

INTRODUCTION

Most French conventional railway track was constructed by putting the ballast layer on the subgrade soil directly. Due to the long-term train circulation, a layer namely interlayer was naturally formed in the substructure, mainly by the interpenetration of ballast and subgrade. Considering its high dry density (2.4 Mg /m^3) and high bearing capacity [1], the French railway company (SNCF) has decided to keep it as part of the substructure in the execution of the track renewal program [2].

Based on the field investigation, the content of ballast grains was found to decrease over depth [1]. Globally, the interlayer can be separated into two parts: the upper part dominated by ballast grains and the lower part dominated by fine soils. For the upper part, the effects of fine soils content and water content on the mechanical behavior were studied by Trinh et al. [3], Cui et al. [2], Duong et al. [4-6] and Lamas-Lopez et al. [7, 8] by performing monotonic and cyclic triaxial tests. In order to extend the study to the whole interlayer, Wang et al. [9-11] and Qi et al. [12] investigated the effect of coarse grain content f_v (volumetric ratio of coarse grains to total sample) on the mechanical behavior. Results revealed existence of a characteristic volumetric coarse grain content $f_{v\text{-cha}}$, below which the soil was characterised by a fine matrix with coarse grains floating in it, while beyond which the soil was characterised by a coarse grain skeleton. It is worth noting that in the previous studies, the effect of f_v on the mechanical behavior was investigated under constant water content conditions. This is obviously not the field condition where the water content varies depending on the weather conditions, resulting in changes in mechanical behavior. Therefore, from a practical point of view, it appears essential to investigate the effect of water content on the mechanical behavior of interlayer soil.

There are several studies addressing the effect of coarse grain content on the mechanical behavior of soil. Seif El Dine et al. [13] worked on sandy matrix with f_v of gravels, showing an increase of shear strength with the increase of f_v. However, Vallejo [14] showed an opposite trend when the mass proportion of coarse particles was beyond 65% for a mixture of rock and sand. It is worth noting that the fines involved in their studies were cohesionless soils like sand and glass beads, which did not represent the natural fine soils in the interlayer. Wang et al. [9-11] studied the effect of f_v on the static and dynamic responses of interlayer soil, and identified a characteristic value $f_{v\text{-cha}}$ that could be used to differentiate two distinct soil fabrics. Qi et al. [12] investigated the effect of the coefficient of uniformity C_u of coarse grains on the mechanical behavior of interlayer soils, and found that the decrease of C_u led to an increase of $f_{v\text{-cha}}$. A few studies were undertaken to investigate the water content effect on the mechanical behavior of substructure soils in terms of shear strength, resilient modulus, etc. Trinh et al. [3] investigated the effect of water content on the mechanical behavior of fouled ballast at different water contents and found that the lower the water content, the higher the shear strength. Duong et al. [6] studied the effect of water content on the resilient modulus of the upper part interlayer soil by large-scale cyclic triaxial tests, and reported that the increase of water content gave rise to a decrease of resilient modulus. To the author's knowledge, there has been no work addressing the effect of water content on $f_{v\text{-cha}}$.

In this study, the effect of water content on the mechanical behavior of the interlayer soil at various f_v values was investigated by performing monotonic triaxial tests under different confining pressures. Three water contents (17.6%, 10.6%, and 7.0%), five coarse grain contents (0%, 10%, 20%, 35%, and 45%) and three confining pressures (30 kPa, 60 kPa and 120 kPa) were considered. The mechanical properties including Young's modulus E_0, Poisson's ratio v, dilatancy angle ψ, friction angle φ and cohesion c were analyzed. The results obtained allowed the effect of water content on the characteristic volumetric coarse grain content $f_{\text{v-cha}}$ to be clarified.

MATERIALS AND METHODS

Materials and sample preparation

Since it was difficult to obtain intact interlayer soil, the studied soil was reconstituted in the laboratory. For the fines, in order to simulate the grain size distribution of fine soils from 'Senissiat site' (Fig. 1), nine different commercial soils including sand and clay were mixed, with the pre-determined proportions shown in Table 1. The liquid limit and plasticity index of the reconstituted fine soil were 32% and 20%, respectively defining the fine soil as CL according to the universal soil classification system (Fig. 2). A good agreement between real fine soil and reconstituted fine soil was observed in terms of grain size distribution (Fig. 1), liquid limit and plasticity index (Fig. 2). Standard Proctor compaction was performed following ASTM D698-12 [15] for the reconstituted fine soil (Fig. 3), allowing an optimum water content $w_{\text{opt-f}} = 13.7\%$ and a maximum dry density $\rho_{\text{dmax-f}} = 1.82\ \text{Mg/m}^3$ to be identified.

For the coarse grains, following the parallel similitude method adopted by Wang et al. [10] and Qi et al. [12], micro-ballast was prepared to represent the real ballast by using three granular materials G 4-10, HN 2-4 and G 10-20, as shown in Fig. 4. In order to quantify the amount of micro-ballast in a sample, a parameter namely volumetric coarse grain content f_v [9-13] was adopted:

$$f_v = V_{in} / V_{total} \quad (1)$$

where V_{in} and V_{total} represent the coarse grain volume and the total sample volume, respectively. Note that the total sample volume V_{total} was composed of the coarse grain volume V_{in} and the fine soil volume V_{fines}. The dry density of fine soil in all samples was controlled at $\rho_{dmax\text{-}f}$ = 1.82 Mg/m^3 (Table 2). At a given f_v value, the dry mass of coarse grain, the dry mass of fine soil and the water content contained in the fine soil can be calculated. Details about the calculation could be found in Wang et al. [10].

For the preparation of samples at target f_v and w_f, the fine soil was prepared at optimum water content $w_{opt\text{-}f}$ = 13.7%, then stored in a container for 24 h for moisture homogenization. The fine soil was then mixed with micro-ballast grains thoroughly to reach the target f_v value. After that, the soil mixture was dynamically compacted in three layers to reach the size of 100 mm diameter and 200 mm height. Note that at a given compaction effort, the dry density of fine soils changes with the variation of coarse grain content f_v. Since the dry density of fine soil in all samples was controlled at $\rho_{dmax\text{-}f}$ = 1.82 Mg/m^3, the compaction efforts was higher for the samples at higher f_v values. As a result, higher ρ_d values were obtained for the samples with higher f_v values, as shown in Table 2.

After reaching the target f_v value, either a wetting or a drying process was adopted to obtain the target w_f: w_1 = 17.6% on the wet side of optimum; w_2 = 10.6% and w_3 = 7.0% on the dry side of optimum. In the case of drying process, considering that a too fast drying would lead to sample damage by fissuring, a milder drying method was performed: the sample was exposed to the air in the laboratory for 1 h each time, and then enveloped with plastic film for equilibration. The time of equilibration needed was determined by measurement of suction and water content in three positions: in the center, ½ r and r, with r being radius of the sample. The results obtained showed that 7 h was required for reaching reasonable equilibration in terms of suction and water content (Table 3). In the case of wetting process, 10 g water was sprayed on the sample each time prior to covering it with plastic film for equilibration. The same equilibration time of at least 7 h was adopted.

When wetting or drying to a target w_f, the volume of sample was measured by means of a caliper. The volume changes from initial water content $w_{opt\text{-}f}$ = 13.7% to different target w_f values are presented in Fig. 5. It appears that at a given f_v value, an increase of water content from $w_{opt\text{-}f}$ = 13.7% to w_1= 17.6% led to sample swelling, while a decrease of water content from $w_{opt\text{-}f}$ = 13.7% to w_2= 10.6% or w_3= 7.0% led to sample shrinkage. Moreover, under a given water content, the sample exhibited lower swelling-shrinkage with higher f_v values, illustrating the sensitivity of fine soil to water content changes. The measured dry densities of samples after wetting or drying are shown in Table 2.

Monotonic triaxial tests

The mechanical behavior of soil at five different f_v values (0%, 10%, 20%, 35%, and 45%) and three different w_f contents (17.6%, 10.6%, and 7.0%) was investigated by monotonic triaxial tests, under three different σ_3 values (30 kPa, 60 kPa and 120 kPa). Note that all samples were prepared to reach the target water contents (w_1 = 17.6% on the wet side, or w_2 = 10.6% and w_3 = 7.0% on the dry side) prior to starting the test. For the samples at w_1 = 17.6% (S_r = 100%), an overnight consolidation under the corresponding confining pressure was adopted prior to shearing, to ensure the dissipation of pore water pressure. On the contrary, for the samples at w_2 = 10.6% (S_r = 60%) or w_3 = 7.0% (S_r = 40%), after an application of σ_3, the sample was directly sheared, because only air was expected to be expelled. A shear rate as low as 0.1mm/min was adopted for all tests. The tests ended when a peak deviator stress appeared or the axial strain ε_1 reached 15% in case without occurrence of peak deviator stress.

EXPERIMENTAL RESULTS

Variation of shear behavior with f_v

The variations of deviator stress q and volumetric strain ε_v with axial strain ε_1 for samples at w_1 = 17.6% and five different f_v values are depicted in Fig. 6. It can be observed from Figs. 6a$_1$-6a$_3$ that under a given confining pressure σ_3 value, the maximum deviator stress q_{max} increased slowly with the increase of f_v for $f_v \leq 20\%$, while the increase of q_{max} was more pronounced for $f_v \geq 35\%$. The similar phenomena can be observed for the case of w_2 = 10.6% and w_3 = 7.0%.

In Fig. 6b$_1$, pure contractancy behaviour was observed for samples at $f_v \leq 20\%$, while for samples at $f_v \geq 35\%$, a behavior of contractancy followed by dilatancy was identified. Moreover, the larger the f_v value, the more pronounced the dilatancy behaviour. This dilatancy was however reduced by the increase of confining pressure: when σ_3 was increased from 60 kPa (Fig. 6b$_2$) to 120 kPa (Fig. 6b$_3$), the contractancy increased and the dilatancy decreased.

Variation of maximum deviator stress q_{max} with w

Fig. 7 depicts the variations of q_{max} against f_v at different σ_3 values for three different water contents. In the case of w_1 = 17.6% (Fig. 7a), it appeared that under a given σ_3 value, the variation of q_{max} followed a bi-linear pattern with two different slopes, which defined a characteristic volumetric coarse grain content $f_{\text{v-cha}}$. Moreover, similar $f_{\text{v-cha}}$ values (around 25%) could be identified for the three different σ_3 values. Physically, the $f_{\text{v-cha}}$ value distinguished two different soil fabrics: when $f_{\text{v}} \leq f_{\text{v-cha}}$, the soil fabric was governed by fine soil dominated structure, while when $f_{\text{v}} \geq f_{\text{v-cha}}$ it was governed by coarse grain dominated structure, in agreement with the observations by Wang et al. [10] and Qi et al. [12].

The same phenomena were observed for the two other water contents: w_2 = 10.6% (Fig. 7b) and w_3 = 7.0% (Fig. 7c). For each water content, q_{max} varies in a bi-linear fashion with with f_{v}, defining a $f_{\text{v-cha}}$ value which is independent of the σ_3 value. The values of $f_{\text{v-cha}}$ were 29% and 33% for w_2 = 10.6% and w_3 = 7.0%, respectively. Comparison of the $f_{\text{v-cha}}$ values at different water contents showed that $f_{\text{v-cha}}$ increased with the decrease of water content.

Variation of Young's modulus E_0 with w

In this study, the Young's modulus E_0, was defined as the ratio of deviator stress to axial strain from 0% to 1%. Fig. 8 shows the variations of E_0 with f_v under different σ_3 values for the three water contents. The effect of w on Young's modulus E_0 can be clearly observed: at a given f_v and σ_3, E_0 increased with the decrease of water content. This was attributed to the increase of suction with the decrease of water content. At a given water content, a bi-linear fitting could be also applied to represent changes of E_0 with f_v for all σ_3 values. This also defined a characteristic volumetric coarse grain content $f_{v\text{-cha}}$, which was independent of σ_3. As far as the variation of $f_{v\text{-cha}}$ with w was concerned, it appeared from Fig. 8 that $f_{v\text{-cha}}$ increased with the decrease of w: $f_{v\text{-cha}}$ was around 25% for $w_1 = 17.6\%$ (Fig. 8a), 29% for $w_2 = 10.6\%$ (Fig. 8b) and 33% for $w_3 = 7\%$ (Fig. 8c), which agreed well with the previous observation while studying the effect of water content on q_{max} in Fig. 7.

Variations of Poisson's ratio v and dilatancy angle ψ with w

Based on the volumetric strain-axial strain curves, the Poisson's ratio v and the dilatancy angle ψ were determined using respectively Eqs. (1) and (2) [16]:

$$v = (1 - k_c)/2 \tag{1}$$

$$\sin \psi = k_D / (-2 + k_D) \tag{2}$$

where k_c and k_D are the slopes of volumetric strain-axial strain curves in the contractancy phase and dilatancy phase, respectively.

Fig. 9 depicts the variations of Poisson's ratio v versus f_v at different σ_3 values for three water contents. At $w_1 = 17.6\%$ (Fig. 9a), v was not significantly influenced by σ_3 and f_v, with the values fluctuating around $v = 0.36$. The values of v at $f_v \leq 20\%$ were slightly larger than those at $f_v \geq 35\%$. This was due to the transition of soil fabric from fine soils dominated structure to coarse grains dominated structure, which resulted in the increase of soil stiffness and the decrease of horizontal strain. Moreover, the difference of v between $f_v \leq 20\%$ and $f_v \geq 35\%$ decreased with the decrease of water content. The average value of v was 0.21 at $w_2 = 10.6\%$ (Fig. 9b) and 0.19 at $w_3 = 7.0\%$ (Fig. 9c). At $w_3 = 7.0\%$, the v remained almost unchanged with the increase of f_v. Overall, it appeared that the average value of v decreased with the decreasing water content, suggesting that the lateral strain was reduced by the increase of suction or decrease of water content.

The effect of w on the dilatancy angle ψ can be clearly observed in Fig. 10: under given f_v and σ_3 values, the ψ increased with the decrease of w. This could be attributed to the aggregation of fine soil induced by the increase of suction. Indeed, a lower water content would generate a higher suction. In that case, the fine soils behaved more like granular materials, exhibiting more dilatancy behavior, as shown by Cui and Delage [17] and Ng et al. [18].

As shown in Fig. 10a ($w_1 = 17.6\%$), no dilatancy behavior was observed for f_v varying from 0% to 20% at all σ_3 values, whereas an obvious dilatancy behaviour was observed for $f_v = 35\%$ at $\sigma_3 = 30$ kPa and for $f_v = 45\%$ at all σ_3 values. In addition, in Fig. 10b and Fig. 10c, a distinct change of ψ was observed from $f_v \leq 20\%$ to $f_v \geq 35\%$, defining a value of characteristic volumetric coarse grain content $f_{\text{v-cha}} \approx 29\%$ at $w_2 = 10.6\%$ and $f_{\text{v-cha}} \approx 33\%$ at $w_3 = 7.0\%$. This increase of $f_{\text{v-cha}}$ with the decrease of water content was consistent with the observation of water effect on q_{max} and E_0.

Variations of cohesion c and friction angle φ with w

The values of cohesion c and friction angle φ were determined based on the peak deviator stress values. Fig.11 depicts the variation of cohesion c with w. It can be observed that at a given f_v, the cohesion c increased with the decrease of water content. This could be attributed to the effect of suction on the fine soil.

For the friction angle φ, Fig.12 shows that φ increased with the decrease of w. This confirmed the aggregation phenomenon with the decrease of w for the fine soils. The similar observation was made by Zhao et al. [19] while studying the shear strength of a mixture of sand, silt and gravel. Moreover, under a given w, a bi-linear pattern of increasing trend with f_v was observed for φ. A value of $f_{\text{v-cha}}$ could be thus identified for each water content: $f_{\text{v-cha}} \approx 25\%, 29\%, 33\%$ for $w = 17.6\%, 10.6\%, 7.0\%$, respectively, in agreement with the effects of water content on q_{max}, E_0 and ψ.

DISCUSSIONS

The test results showed that the value of $f_{\text{v-cha}}$ increased with the decrease of water content, as shown in Table 4. Wang et al. [10] obtained a value of $f_{\text{v-cha}}$ equal to 27% at the optimum water content $w_{\text{opt-f}} = 13.7\%$, which came to confirm the observation made in this study.

As mentioned before, the $f_{\text{v-cha}}$ corresponded to the transition of soil fabric: when $f_{\text{v}} \leq f_{\text{v-cha}}$, the soil fabric was the fine soils dominated structure, while when $f_{\text{v}} \geq f_{\text{v-cha}}$, the soil fabric changed to the coarse grains dominated structure. In other words, the $f_{\text{v-cha}}$ represented the minimum f_{v} value needed for forming a coarse grains dominated structure. When $f_{\text{v}} \geq f_{\text{v-cha}}$, two categories of fine soils were expected, namely a first category of dense fine soils situated between coarse grains and a second category of loose fine soils situated in the macro-pores surrounded by coarse grains. The former contributed to the loading-bearing skeleton of coarse grains, whereas the latter contributed little, as concluded by de Frias Lopez [20] through discrete element analysis.

The variation of $f_{\text{v-cha}}$ with w could be attributed to the swelling upon wetting and shrinkage upon drying of these two categories of fines. With the decrease of water content, the two categories of fine soils would shrink. The shrinkage of the first category of fines would lead to a decrease of macro-pores between coarse grains, while the shrinkage of the second category would lead to an increase of macro-pores surrounded by coarse grains. As the density was expected to be higher and the quantity was expected to be smaller for the first category of fines, the decrease of macro-pores volume due to the shrinkage of the first category of fines was expected to be much smaller than the increase of macro-pores volume due to the shrinkage of the second category of fines. This was supported by the observation from Zhang and Li [21] using mercury intrusion porosimetry, who studied the fine/coarse soil mixture and reported that the structure supported by coarse grains was stable, and thus the shrinkage of clayey soils gave rise to an increase of the volume of macro-pores surrounded by coarse particles. The effect of shrinkage of fine soils was also observed by Fies et al. [22] for the ternary mixtures of sand, silt and clay soils. They reported that when the fine fraction contained larger than 25% clay content, the shrinkage of fine fraction gave rise to the formation of macro-pores among the coarse fraction. It is worth noting that in this study, 30% of clay content of Speswhite and Bentonite were shown in Table 1 for the fine fraction, which contributed to the formation of macro-pores in the coarse grain skeleton. Thus, with the increase of volume of macro-pores, more coarse grains were needed to constitute a global skeleton. This is characterized by the increase of $f_{\text{v-cha}}$ value.

CONCLUSIONS

The effect of w on the mechanical behavior of interlayer soil at various f_v was investigated by monotonic triaxial tests. Three water contents (w = 17.6%, 10.6%, and 7.0%), five volumetric coarse grain contents (f_v = 0%, 10%, 20%, 35% and 45%) and three confining pressures (σ_3 = 30 kPa, 60 kPa and 120 kPa) were considered. The obtained results allowed the following conclusions to be drawn.

The decrease of water content led to an increase of the peak deviator stress $q_{\max}$ and the Young's modulus E_0. This could be explained by the effect of suction with the decrease of water content. The Poisson's ratio v was found to decrease with the decrease of water content, because the horizontal deformation was reduced by the increase of suction. The dilatancy angle ψ and the friction angle φ were found to increase with the decrease of water content. This was attributed to the aggregation of fine soils induced by the increase of suction, enhancing the dilatancy behavior and the friction of soil. A larger cohesion c was observed at lower w, also due to the effect of suction in fine soils.

The variation of $q_{\max}$, E_0, ψ, and φ with f_v followed a bi-linear pattern, defining a same characteristic $f_{v\text{-cha}}$ value for a given w value: $f_{v\text{-cha}} \approx 25\%$, 29% and 33% for $w = 17.6\%$, 10.6% and 7.0%, respectively. The value of $f_{v\text{-cha}} \approx 27\%$ at $w_{opt} = 13.7\%$ reported by Wang et al. (2018a) came to support this observation. This was attributed to the swelling upon wetting and shrinkage upon drying of two categories of fine soils: a first category of dense fine soil situated between coarse grains and a second category of loose fine soil situated in the macro-pores surrounded by coarse grains. With the decrease of water content, the two categories of fine soils would shrink. Moreover, the shrinkage of the first category of fines would lead to a decrease of macro-pores between coarse grains, while the shrinkage of the second category would lead to an increase of macro-pores surrounded by coarse grains. As the decrease of macro-pores volume due to the shrinkage of the first category of fines was expected to be much smaller than the increase of macro-pores volume due to the shrinkage of the second category of fines, the global macro-pores volume was increasing with the decrease of water content. In that case, more coarse grains were needed to constitute a global skeleton, leading to an increase of $f_{v\text{-cha}}$.

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REFERENCES

[1] V. N. Trinh, Comportement hydromécanique des matériaux constitutifs de plateformes ferroviaires anciennes. PhD Thesis, Ecole Nationale des Ponts et Chaussées, Université Paris-Est, 2011.

[2] Y.J. Cui, T.V. Duong, A.M. Tang, J.C. Dupla, N. Calon, A. Robinet, Investigation of the hydro-mechanical behaviour of fouled ballast, Journal of Zhejiang University Science A. 14(4) (2013) 244-255.

[3] V.N. Trinh, A.M. Tang, Y.J. Cui, J.C. Dupla, J. Canou, N. Calon, L. Lambert, A. Robinet, O. Schoen, Mechanical characterisation of the fouled ballast in ancient railway track substructure by large-scale triaxial tests, Soils and foundations. 52(3) (2012) 511-523.

[4] T.V. Duong, A.M. Tang, Y.J. Cui, V.N. Trinh, J.C. Dupla, N. Calon, J. Canou, A. Robinet, Effects of fines and water contents on the mechanical behavior of interlayer soil in ancient railway sub-structure, Soils and foundations. 53(6) (2013) 868-878.

[5] T.V. Duong, Y.J. Cui, A.M. Tang, J.C. Dupla, J. Canou, N. Calon, A. Robinet, Investigating the mud pumping and interlayer creation phenomena in railway sub-structure, Engineering geology. 171 2014 45-58.

[6] T.V. Duong, Y.J. Cui, A.M. Tang, J.C. Dupla, J. Canou, N. Calon, A. Robinet, Effects of water and fines contents on the resilient modulus of the interlayer soil of railway substructure, Acta Geotechnica. 11(1) 2016 51-59.

[7] F. Lamas-Lopez, S.C. d'Aguiar, A. Robinet, Y.J. Cui, N. Calon, J. Canou, J.C. Dupla, A.M. Tang, In-situ investigation of the behaviour of a French conventional railway

platform, In Proceedings of the transportation research board 94th annual meeting. Washington, DC (2015) 15-1076.

[8] F. Lamas-lopez, Field and laboratory investigation on the dynamic behavior of conventional railway track-bed materials in the context of traffic upgrade. PhD Thesis, Ecole Nationale des Ponts et Chaussées, Université Paris-Est, 2016.

[9] H.L. Wang, Y.J. Cui, F. Lamas-Lopez, J.C. Dupla, J. Canou, N. Calon, G. Saussine, P. Aimedieu, R.P. Chen, Effects of inclusion contents on resilient modulus and damping ratio of unsaturated track-bed materials, Canadian Geotechnical Journal. 54(12) (2017) 1672-1681.

[10] H.L. Wang, Y.J. Cui, F. Lamas-Lopez, N. Calon, G. Saussine, J.C. Dupla, J. Canou, P. Aimedieu, R.P. Chen, Investigation on the mechanical behavior of track-bed materials at various contents of coarse grains, Construction and Building Materials. 164 (2018) 228-237.

[11] H.L. Wang, Y.J. Cui, F. Lamas-Lopez, J.C. Dupla, J. Canou, N. Calon, G. Saussine, P. Aimedieu, R.P. Chen, Permanent deformation of track-bed materials at various inclusion contents under large number of loading cycles, Journal of Geotechnical and Geoenvironmental Engineering. 144(8) (2018) 04018044.

[12] S. Qi, Y.J. Cui, R.P. Chen, H.L. Wang, F. Lamas-Lopez, P. Aimedieu, J.C. Dupla, J. Canou, G. Saussine, Influence of grain size distribution of inclusions on the mechanical behaviours of track-bed materials, Géotechnique. (2019) 1-10.

[13] B. Seif El Dine, J. C. Dupla, R. Frank, J. Canou, Y. Kazan, Mechanical characterization of matrix coarse-grained soils with a large-sized triaxial device, Canadian Geotechnical Journal. 47(4) (2010) 425-438.

[14] L.E. Vallejo, Interpretation of the limits in shear strength in binary granular mixtures, Canadian Geotechnical Journal. 38(5) (2001) 1097-1104.

[15] ASTM D698-12. Standard test methods for laboratory compaction characteristics of soil using standard effort. ASTM International, West Conshohocken, Pa, 2012)

[16] P.A. Vermeer, R. De Borst, Non-associated plasticity for soils, concrete and rock. HERON, 29(3) (1984) 1-64.

[17] Y.J. Cui, P. Delage, Yeilding and plastic behaviour of an unsaturated compacted silt, Géotechnique. 46(2) (1996) 291-311.

[18] C.W.W. Ng, S. Baghbanrezvan, H. Sadeghi, C. Zhou, F. Jafarzadeh, Effect of specimen preparation techniques on dynamic properties of unsaturated fine-grained soil at high suctions, Canadian Geotechnical Journal. 54(9) (2017) 1310-1319.

[19] H.F. Zhao, L.M. Zhang, D.G. Fredlund, Bimodal shear-strength behavior of unsaturated coarse-grained soils, Journal of geotechnical and geoenvironmental engineering. 139(12) (2013) 2070-2081.

[20] R. de Frias Lopez, J. Silfwerbrand, D. Jelagin, B. Birgisson, Force transmission and soil fabric of binary granular mixtures, Géotechnique. 66(7) (2016)578-583.

[21] L.M. Zhang, X. Li, Microporosity structure of coarse granular soils, Journal of Geotechnical and Geoenvironmental Engineering. 136(10) (2010)1425-1436.

[22] J.C. Fiès, N.D.E., Louvigny, A. Chanzy The role of stones in soil water retention, European Journal of Soil Science. 53(1) (2002) 95-104.

NOTATIONS

c	cohesion
E_0	initial Young’s modulus
f_v	volumetric coarse grain content
$f_\mathrm{v\text{-}cha}$	characteristic volumetric coarse grain content
k_c	slope of volume change curve in the contractancy phase
k_D	slope of volume change curve in the dilatancy phase
ρ_d	dry density of sample
$\rho_\mathrm{dmax\text{-}f}$	maximum dry density of fine soil
q	deviator stress
q_max	peak deviator stress
$w_\mathrm{opt\text{-}f}$	optimum water content of fine soil
w_f	water content of fine soil
ε_a	axial strain
ε_v	volumetric strain
σ_3	confining pressure
φ	friction angle
v	Poisson’s ratio
ψ	dilatancy angle

LIST OF TABLES

Table 1. The constitution of fine soil
Table 2. Experimental program
Table 3. Suction and water content measured at different equilibration times for fine soils
Table 4. $f_{\text{v-cha}}$ values at different water contents

LIST OF FIGURES

Fig. 1. Grain size distribution curves of fine soils (after Wang et al. [10])
Fig. 2. Plasticity of fine soils (after Wang et al. [10])
Fig. 3. Samples states with respect to the compaction curve
Fig. 4. Grain size distribution curves of micro-ballast and ballast (after Wang et al. [10])
Fig. 5. Volume change of samples at different f_v values for the three target water contents
Fig. 6. Results from the tests at w_1=17.6% and different f_v values under: (a$_1$) - (b$_1$) σ_3= 30 kPa; (a$_2$) - (b$_2$) σ_3= 60 kPa; (a$_3$) - (b$_3$) σ_3= 120 kPa
Fig. 7. Variations of peak deviator stress with f_v under different σ_3 values for: (a) w_1 = 17.6%; (b) w_2 = 10.6%; (c) w_3 = 7.0%
Fig. 8. Variations of initial Young's modulus with f_v under different σ_3 values for: (a) w_1 = 17.6%; (b) w_2 = 10.6%; (c) w_3 = 7.0%
Fig. 9. Variations of Poisson's ratio with f_v under different σ_3 values for: (a) w_1 = 17.6%; (b) w_2 = 10.6%; (c) w_3 = 7.0%
Fig. 10. Variations of dilatancy angle with f_v under different σ_3 values for: (a) w_1 = 17.6%; (b) w_2 = 10.6%; (c) w_3 = 7.0%
Fig. 11. Variations of cohesion with f_v under different water contents
Fig. 12. Variations of friction angle with f_v under different water contents

Table 1. The constitution of fine soil

Soil	Mass proportion (%)	Grain size range (mm)
HN34	3.3	0.063 - 0.50
HN31	3.3	0.16 - 0.63
HN0.4-0.8	6.7	0.25 - 1
HN0.6-1.6	6.7	0.32 - 2
HN1-2.5	13.3	0.32 – 3.20
C4	16.7	0.0009 – 0.50
C10	20	0.0009 – 0.25
Speswhite	23.3	0.0003 – 0.01
Bentonite	6.7	0.001 – 0.01

Table 2. Experimental program

f_v (%)	Initial water content $w_{opt\text{-}f}$ (%)	Target w_f (%)	Target S_r (%)	Target $\rho_{dmax\text{-}f}$ (Mg/m^3)	Target ρ_d (Mg/m^3)	Measured ρ_d (Mg/m^3)	Confining pressure σ_3 (kPa)
0	13.7	17.6	100	1.82	1.82	1.80	30 60 120
		10.6	60			1.85	30 60 120
		7.0	40			1.86	30 60 120
10		17.6	100		1.91	1.88	30 60 120
		10.6	60			1.93	30 60 120
		7.0	40			1.94	30 60 120
20		17.6	100		1.99	1.97	30 60 120
		10.6	60			2.01	30 60 120
		7.0	40			2.03	30 60 120
35		17.6	100		2.12	2.11	30 60 120
		10.6	60			2.13	30 60 120
		7.0	40			2.13	30 60 120
45		17.6	100		2.21	2.20	30 60 120
		10.6	60			2.22	30 60 120
		7.0	40			2.23	30 60 120

Note: f_v represents the ratio of volumetric inclusion content to the total volume of the sample [10]. $w_{opt\text{-}f}$, w_f, S_r and $\rho_{dmax\text{-}f}$ represent the optimum water content, the water content, the degree of saturation and the maximum dry density of fine soils, respectively. ρ_d represents the dry density of soil mixture sample. Measured ρ_d represents the dry density of soil mixture sample after wetting or drying from compaction water content $w_{opt\text{-}f}$ to target w_f.

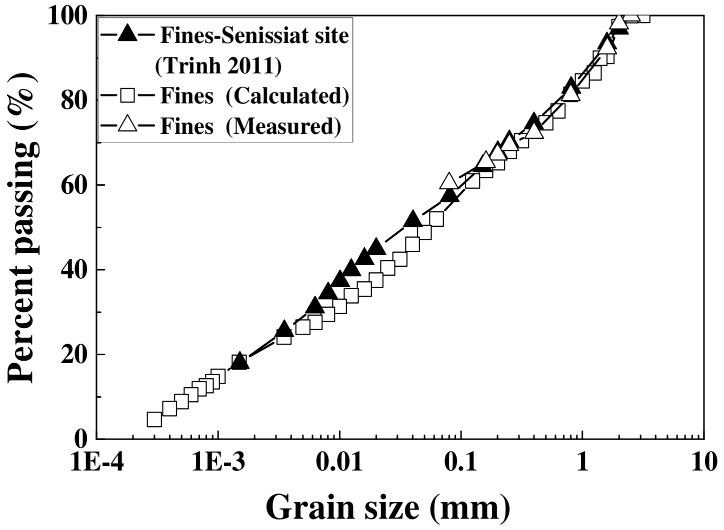
Table 3. Suction and water content measured at different equilibration times for fine soils

Position	Suction (MPa)	Water content (%)	Suction (MPa)	Water content (%)
	After 6h		After 7h	
center	0.33	12.7	0.32	12.9
1/2 r	0.24	13.5	0.35	12.8
r	0.46	13.7	0.33	13.1

Table 4. $f_{\text{v-cha}}$ values at different water contents

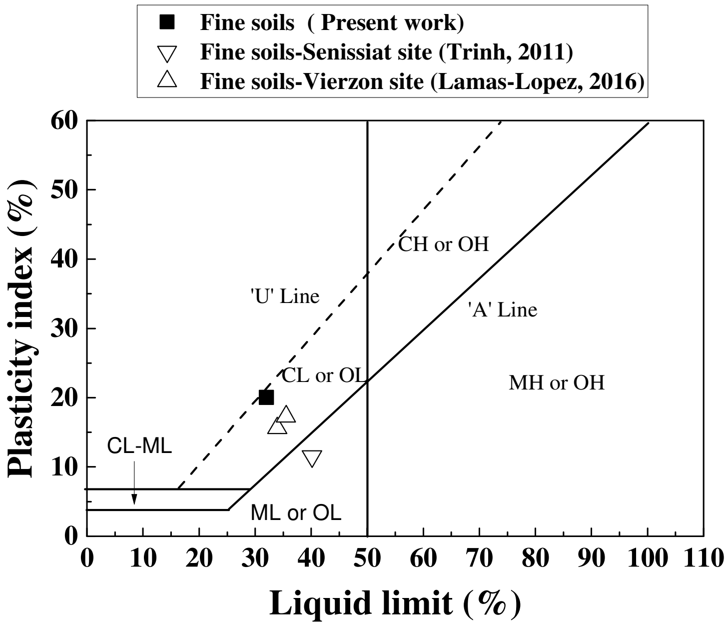
w (%)	17.6	13.7	10.6	7.0
$f_{\text{v-cha}}$ (%)	25	27	29	33

Note: $f_{\text{v-cha}} \approx 27\%$ corresponding to $w = 13.7\%$ was obtained by Wang et al. [10]



394

Fig. 1. Grain size distribution curves of fine soils (after Wang et al. [10])



395

Fig. 2. Plasticity of fine soils (after Wang et al. [10])

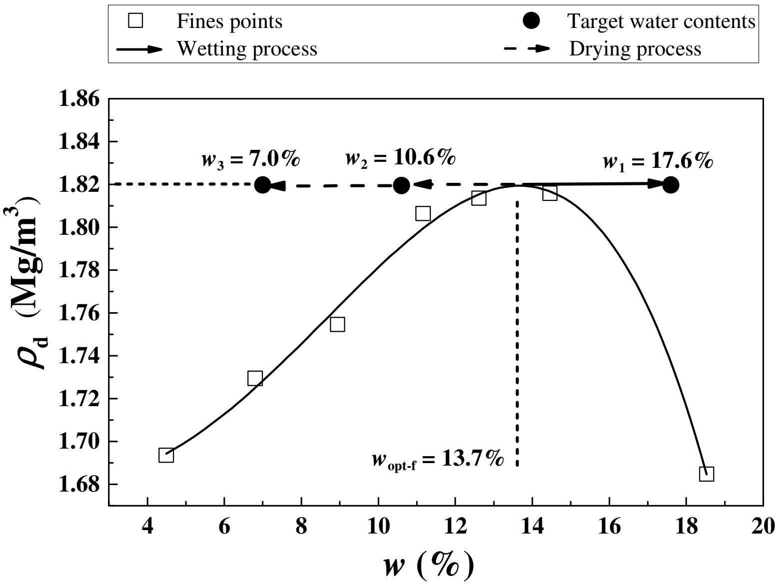


Fig. 3. Samples states with respect to the compaction curve

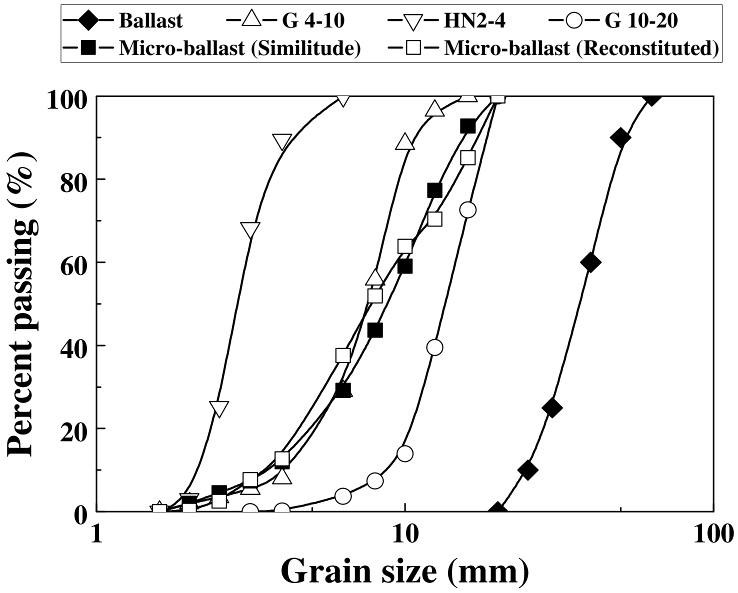


Fig. 4. Grain size distribution curves of micro-ballast and ballast (after Wang et al. [10])

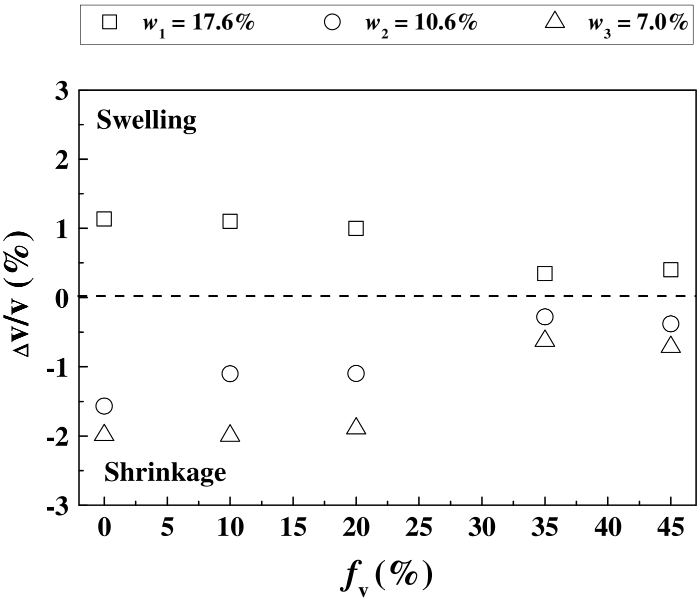
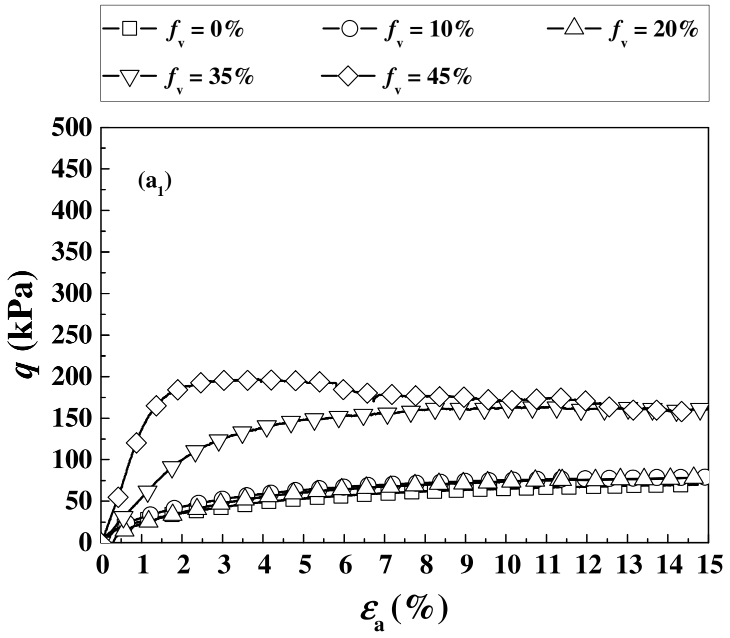
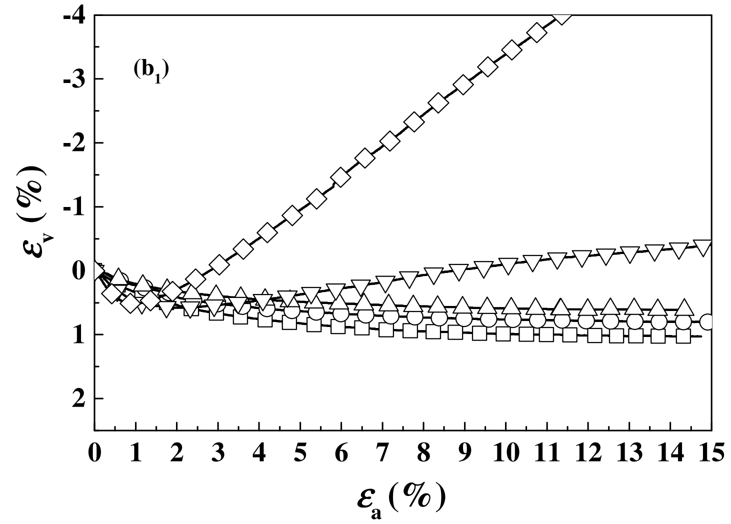
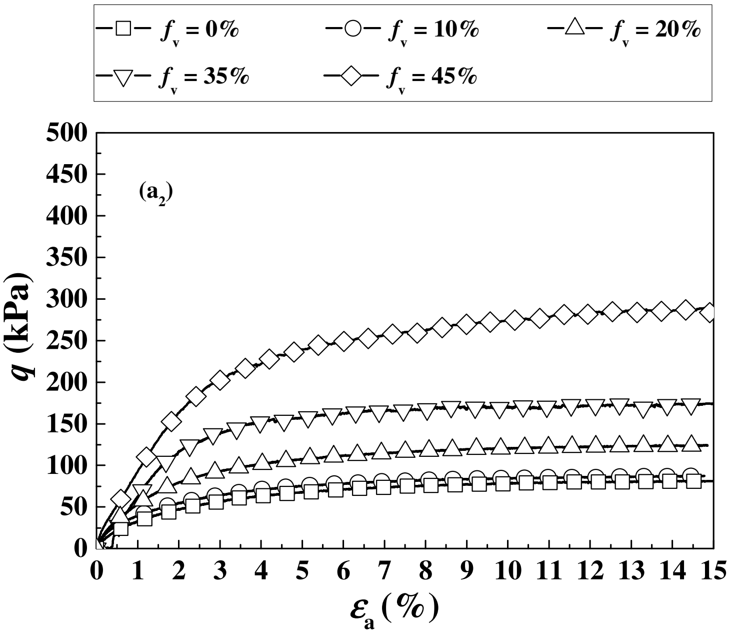
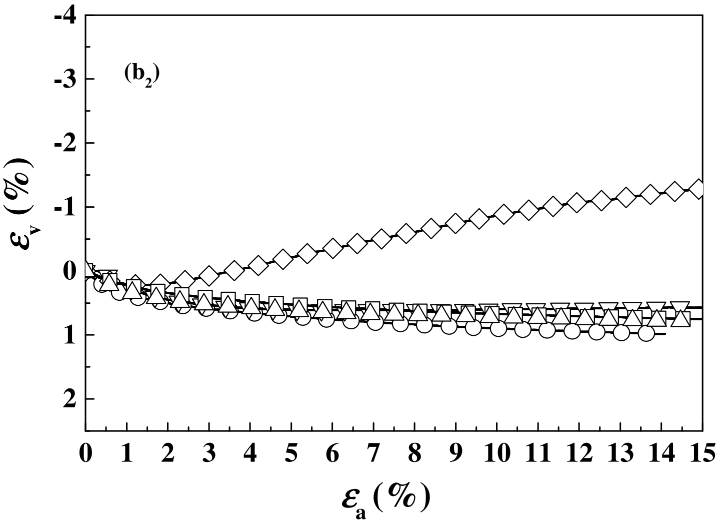


Fig. 5. Volume change of samples at different f_v values for the three target water contents


f_v = 0%
f_v = 10%
f_v = 20%
f_v = 35%
f_v = 45%
(a$_1$)
q (kPa)
500
450
400
350
300
250
200
150
100
50
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
ε_a (%)


(b$_1$)
ε_v (%)
-4
-3
-2
-1
0
1
2
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
ε_a (%)


f_v = 0%
f_v = 10%
f_v = 20%
f_v = 35%
f_v = 45%
(a$_2$)
q (kPa)
0
50
100
150
200
250
300
350
400
450
500
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
ε_a (%)


(b$_2$)
ε_v (%)
-4
-3
-2
-1
0
1
2
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
ε_a (%)

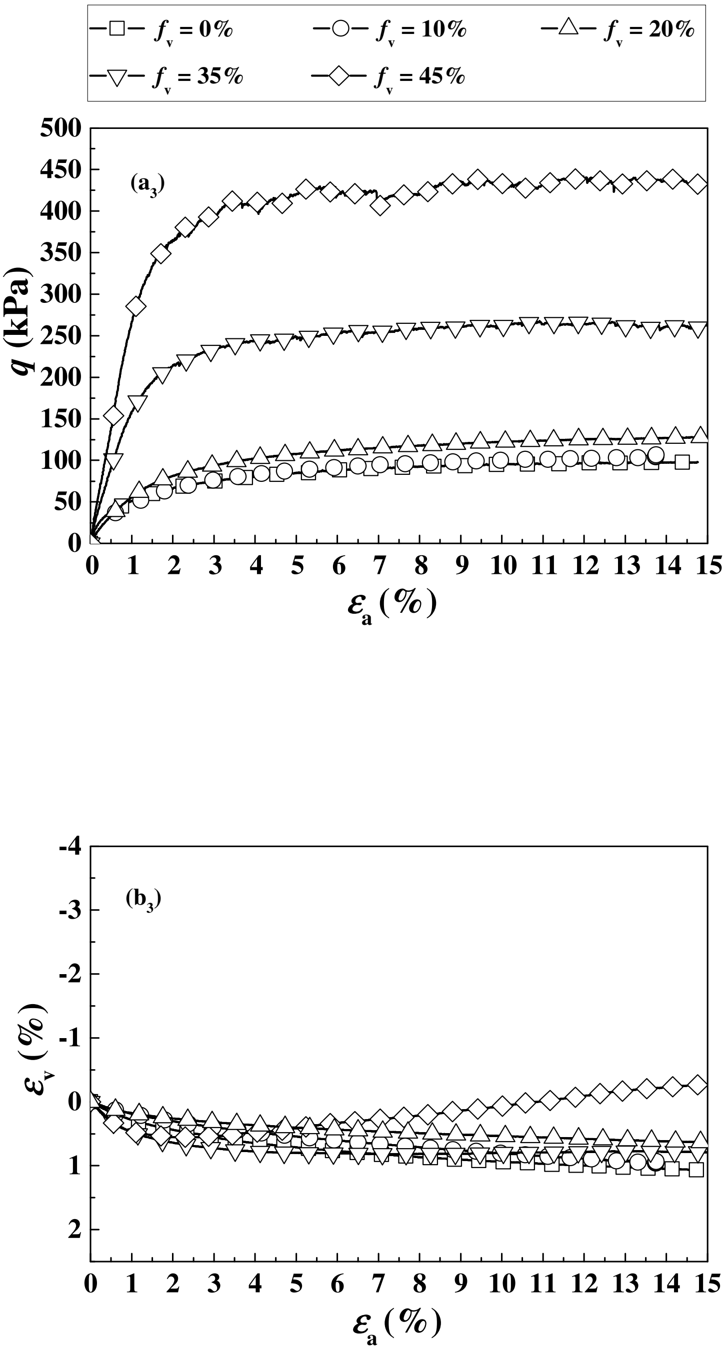
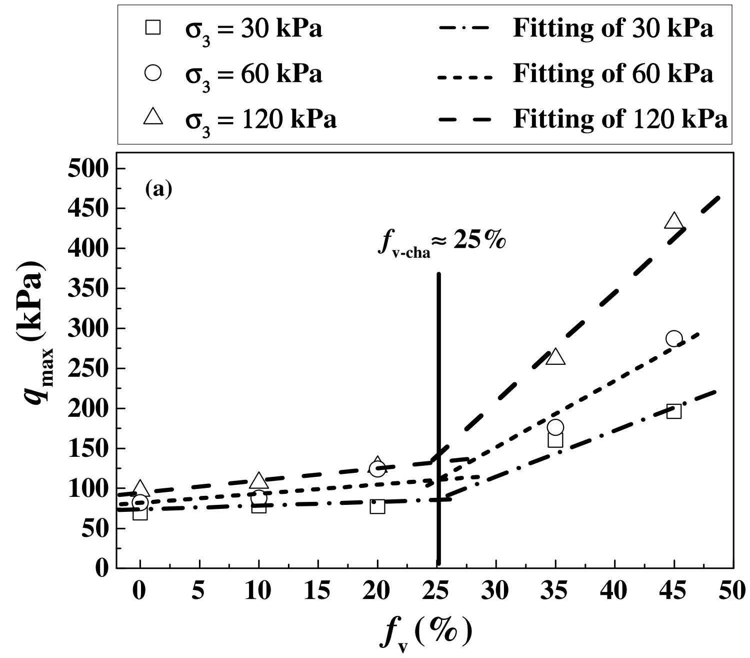
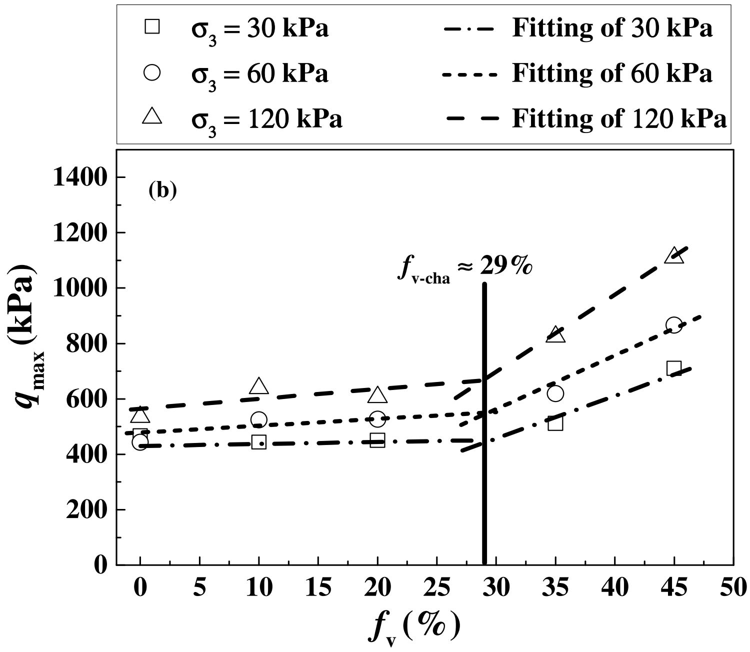


Fig. 6. Results from the tests at w_1=17.6% and different f_v values under:

(a$_1$) - (b$_1$) σ_3= 30 kPa; (a$_2$) - (b$_2$) σ_3= 60 kPa; (a$_3$) - (b$_3$) σ_3= 120 kPa


σ3 = 30 kPa
σ3 = 60 kPa
σ3 = 120 kPa
Fitting of 30 kPa
Fitting of 60 kPa
Fitting of 120 kPa
(a)
fv-cha ≈ 25%
qmax (kPa)
0
50
100
150
200
250
300
350
400
450
500
0
5
10
15
20
25
30
35
40
45
50
fv (%)


σ3 = 30 kPa
σ3 = 60 kPa
σ3 = 120 kPa
Fitting of 30 kPa
Fitting of 60 kPa
Fitting of 120 kPa
(b)
fv-cha ≈ 29%
qmax (kPa)
0
200
400
600
800
1000
1200
1400
0
5
10
15
20
25
30
35
40
45
50
fv (%)

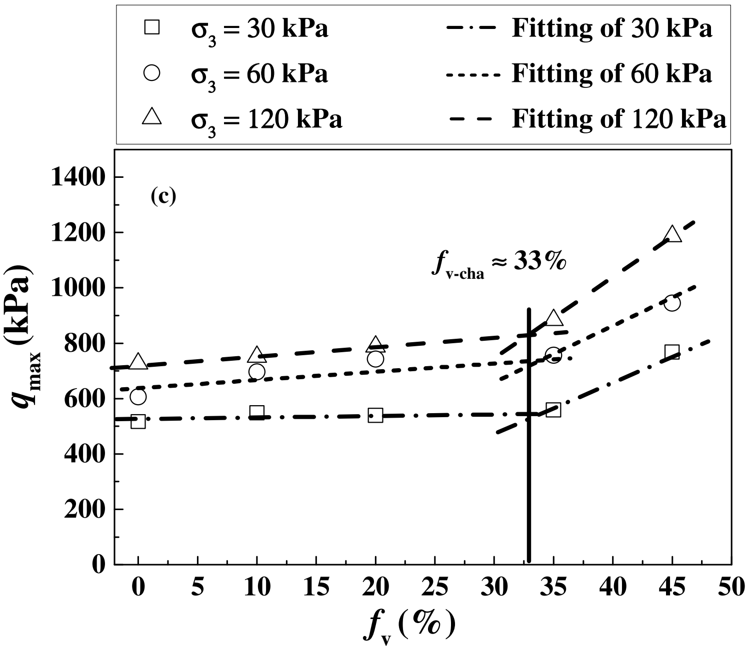
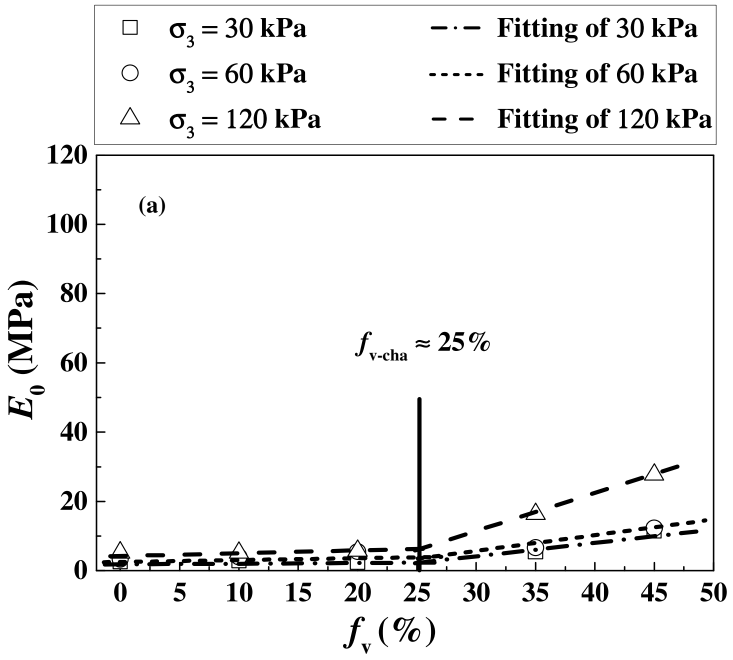


Fig. 7. Variations of peak deviator stress with f_v under different σ_3 values for: (a) $w_1 = 17.6\%$; (b) $w_2 = 10.6\%$; (c) $w_3 = 7.0\%$



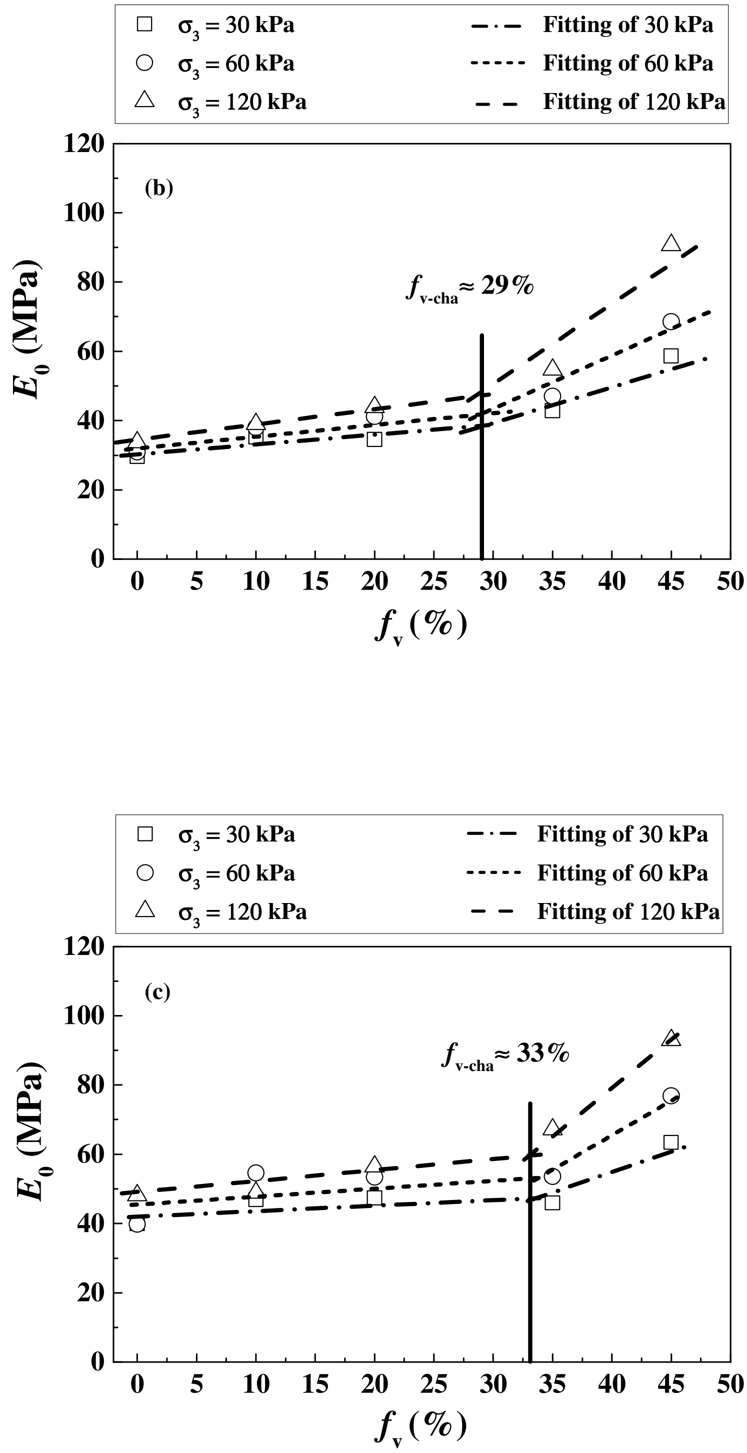
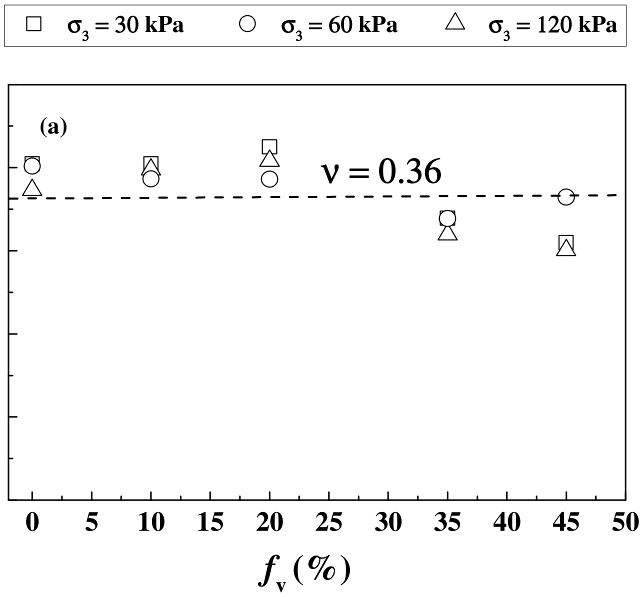
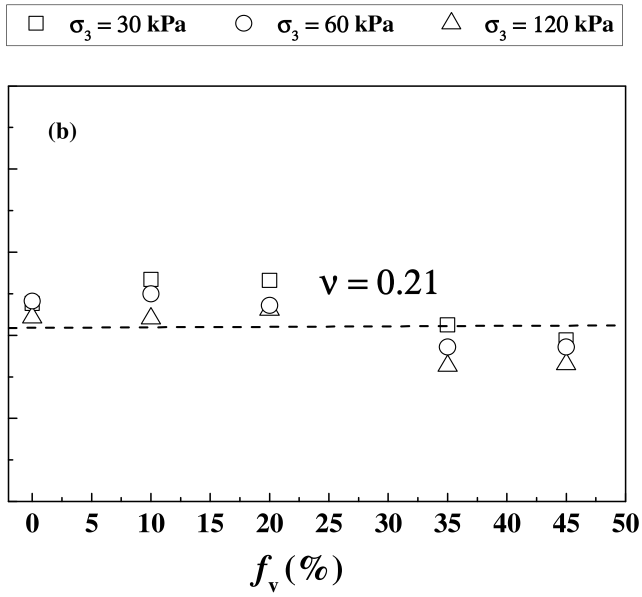


Fig. 8. Variations of initial Young's modulus with f_v under different σ_3 values for:

(a) $w_1 = 17.6\%$; (b) $w_2 = 10.6\%$; (c) $w_3 = 7.0\%$


□ σ_3 = 30 kPa
○ σ_3 = 60 kPa
△ σ_3 = 120 kPa
(a)
ν = 0.36
ν
0.0
0.1
0.2
0.3
0.4
0.5
0
5
10
15
20
25
30
35
40
45
50
f_v (%)


□ σ_3 = 30 kPa
○ σ_3 = 60 kPa
△ σ_3 = 120 kPa
(b)
ν = 0.21
ν
0.0
0.1
0.2
0.3
0.4
0.5
0
5
10
15
20
25
30
35
40
45
50
f_v (%)

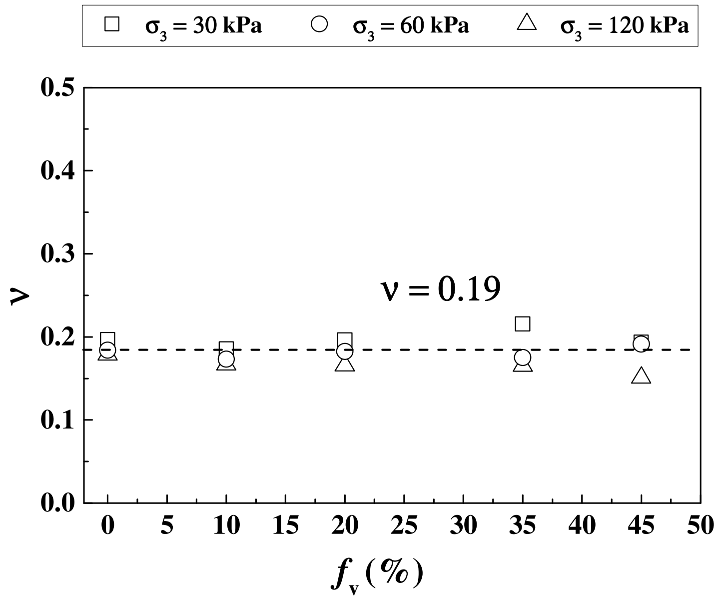
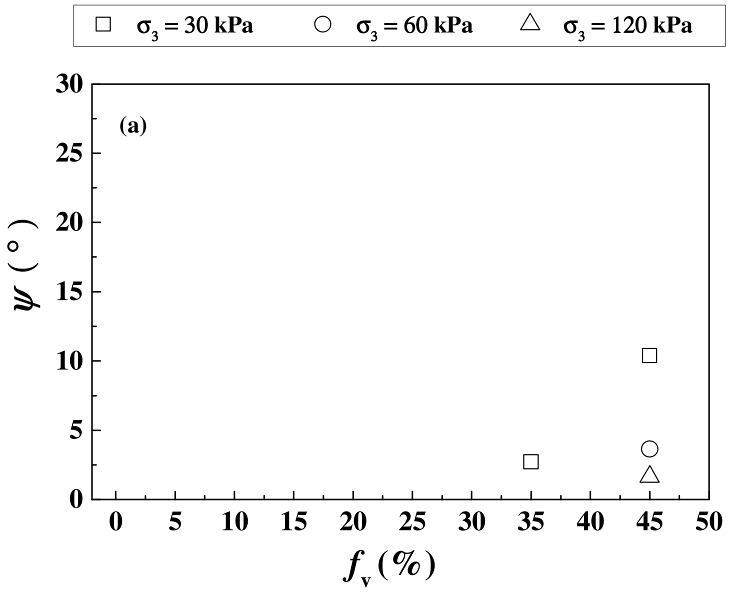


Fig. 9. Variations of Poisson's ratio with f_v under different σ_3 values for: (a) w_1 = 17.6%; (b) w_2 = 10.6%; (c) w_3 = 7.0%



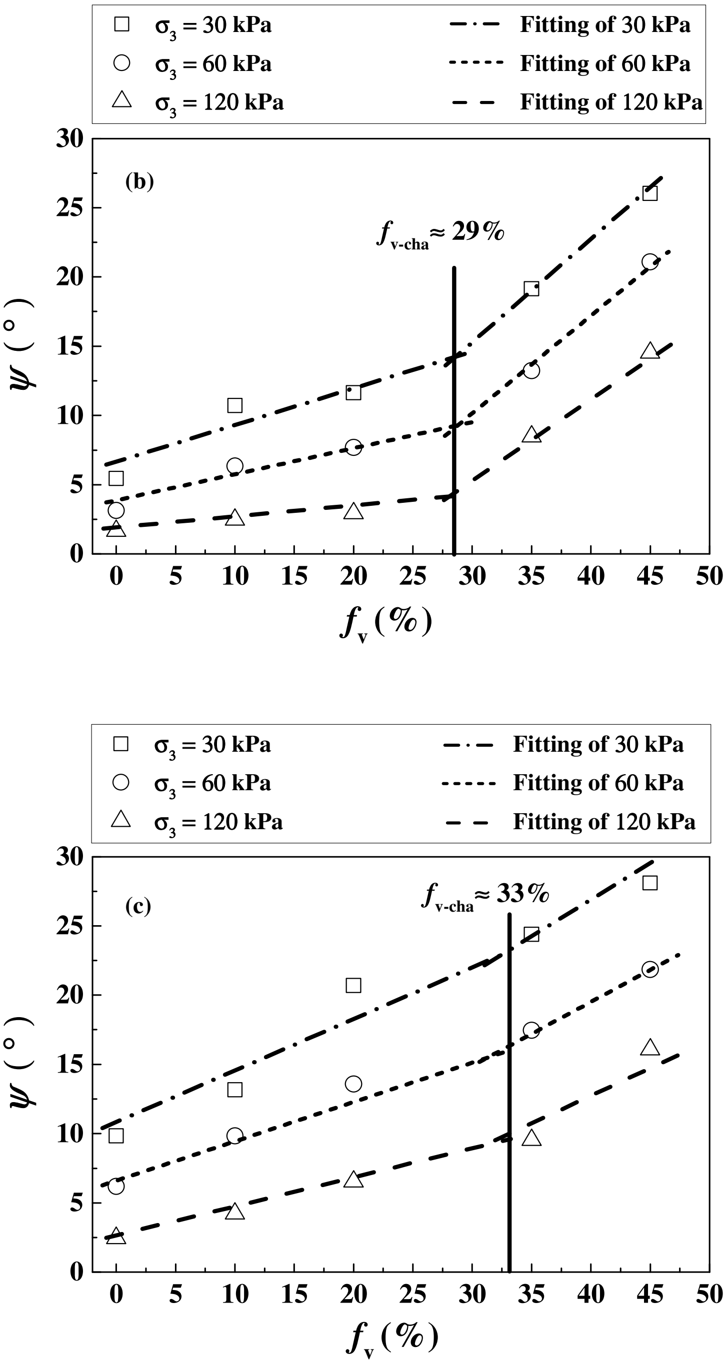


Fig. 10. Variations of dilatancy angle with f_v under different σ_3 values for:

(a) w_1 = 17.6%; (b) w_2 = 10.6%; (c) w_3 = 7.0%

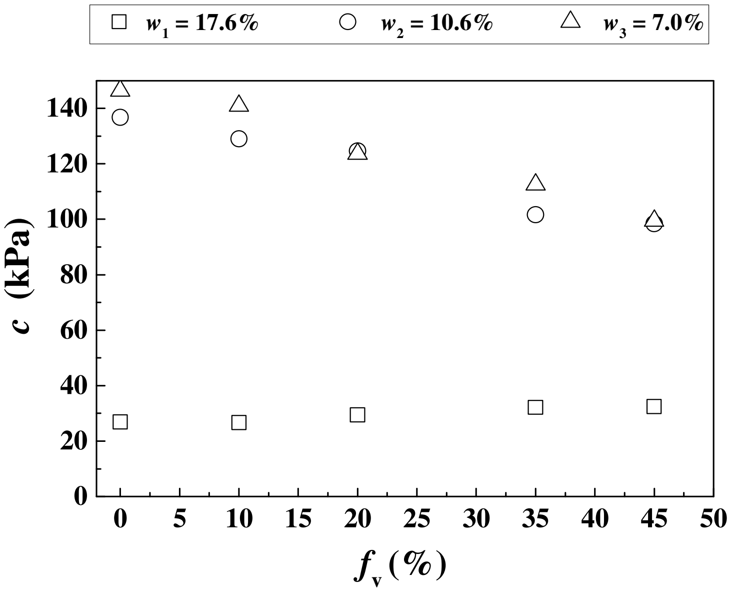


Fig. 11. Variations of cohesion with f_{v} under different water contents

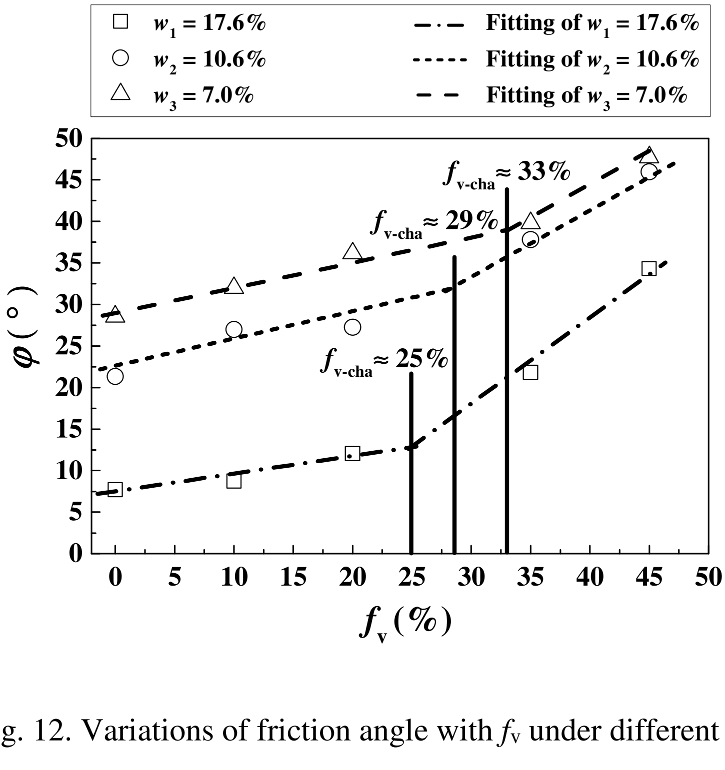


Fig. 12. Variations of friction angle with f_{v} under different water contents