Unsaturated resilient strain behaviours of a granular material

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ABSTRACT: Road pavement structures are generally composed of unsaturated granular materials. The influence of the fine content is significant as well as unsaturated state on the resilient strain behaviour of granular materials for pavements. In this paper, based on the soil water retention curves and repeated load triaxial tests for a granular material with three fine contents, the simple exponential function relationship between resilient strain behaviours and *s/s** values (suction) could be observed, which can reduce the number of tests required to determine the unsaturated resilient strain behaviours of this kind of granular material.

1 GENERAL INSTRUCTIONS

Granular materials are usually used in low traffic pavements as base layer or sub-base layer. During the service life, low-traffic pavements are subjected to variable hydraulic and mechanical impacts, which have a significant influence on mechanical behaviours (both resilient and permanent strain behaviours) of granular materials. In fact, the granular materials in low traffic pavements are commonly in unsaturated states.

Several researches have shown that besides the effect of water content on the mechanical behaviours of the unsaturated granular materials, it is necessary to take into account the effect of suction (Yang et al. 2008, Cary & Zapata, 2011, Nowamooz et al. 2011, Nowamooz et al. 2013, Salour et al. 2014, Han et al. 2015 and Jing et al. 2016, 2017 in press) as well as hydraulic hysteresis (Miller et al. 2008, Yang et al. 2012 and Ho et al. 2014). Different experimental researches showed that the variation of fine content (particles passing the sieve 75 µm or sieve No.200 based on American classification) has also an important effect as well as water content on mechanical behaviours of granular materials as reported by Babić et al. 2000, Duong et al. 2013 and Jing et al. 2016, 2017 in press.

However, the relationship between resilient strain behaviours and unsaturated state with different fine contents has been rarely studied.

In this work, the objective is to study the effect of unsaturated state on the resilient strain behaviours for a granular material constituted of three fine contents in low-traffic pavements.

The soil water retention curves (SWRC) are obtained by suction tests with filter paper method. The resilient strain behaviours of the unsaturated granular material is then studied by a series of repeated load triaxial tests (RLTT).

2 STUDIED MATERIAL

The studied granular material is the Missillac fine sand. It is an alluvial sand coming from the quarry of Missillac in France. The particle size varies between 0 and 4 mm. This sand is used as subgrade soil in low traffic pavements for full-scale pavement tests at IFSTTAR (Institut Français des Sciences et Technologies des Transports, de l'Aménagement et des Réseaux) in Nantes, France. This kind fine sand is sensitive to moisture variation, and its in situ elastic modulus typically varies between 50 and 100 MPa.

2.1 *Particle-size analysis*

In this work, the Missillac sand are studied in three different fine contents, named respectively M4.0, M7.5 and M15.3:

- M4.0 samples contain 4.0% of fine content.
- M7.5 samples contain 7.5% of fine content.
- M15.3 samples contain 15.3% of fine content.

Figure1 shows particle size distribution curves for all of three Missillac sands (XP P94-041,1995). Table 1 presents all of the characteristic parameters of these curves, such as Cc and Cu. The coefficients

Table 1. Characteristics of the studied materials.

Material	Dry density (Mg/m^3)	Fraction (%)				Particle size					Blue value	Classification	
		0/80 µm	0.08/0.4 mm	0.4/2 mm	2/4 mm	d_{60}	d_{30}	d_{10}	C_u	C_c		NF	USCS
M4.0	2.00	4	10	76	5	0.95	0.55	0.30	3.17	1.06	---	B2	SP
M7.5	2.00	7.5	6.5	76	5	1.40	0.60	0.25	5.60	1.03	0.56	B2	SP-SC
M15.3	2.00	15.3	14.7	55	10	0.85	0.40	---	8.50	1.88	0.85	B5	SC

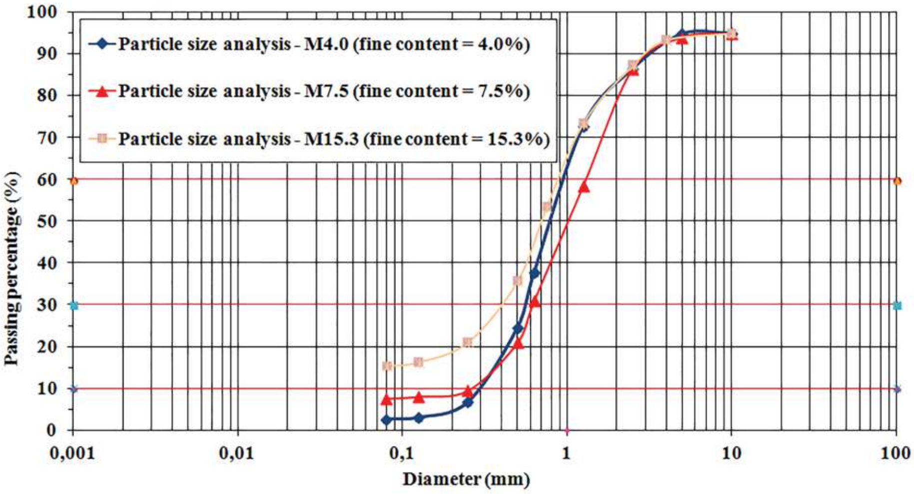

Figure 1. Particle size distribution curves of Missillac sand (M4.0, M7.5 and M15.3).

of curvature (Cc) (estimated between 1 and 3) show a well-graded composition of three studied Missillac sand. The methylene blue values (VBS) of M7.5 and M15.3 (NF P94-068, 1993) are also introduced in Table 1, which shows an obvious increase of VBS value from M7.5 to M15.3. It can be stated that the main component of the fine content for Missillac sand is the clay which is really sensitive to moisture variation.

The materials are also classified based on the VBS values and particle size distribution (NF P11-300, 1992 or USCS ASTM D2487 - 06) as reported in Table 1.

2.2 *Soil water retention curve (SWRC)*

When the soil pores are filled by water and air, the porous material is unsaturated. Unsaturated soils can exert an attraction on water, either by capillary action in the pores, between soil particles, or through physicochemical effects. The pressure difference is referred to as matric suction:

$$s = u_a - u_w \tag{1}$$

where, u_a is pore air pressure and u_w is pore water pressure.

A soil water retention curve (SWRC) is usually used to illustrate the evolution of saturation or water content, as a function of matric suction in unsaturated soil mechanics.

In this study, filter paper method is used to obtain SWRC. For the wetting path, the samples are prepared at a water content ranging from 7% to 12.3% and for the drying path, the samples initially saturated are dried in the ambient temperature (20°) to reach the desired water content from 7% to 12.3 %. All of samples are compacted at an initial dry density ranging of 2±0.06 Mg/m^3. The measured soil water retention curves for M4.0 and M15.3 are illustrated in Figure 2.

In unsaturated soil mechanics, various empirical equations have been suggested to describe the SWRC. Among these equations, the relationships (proposed by van Genuchten, 1980 and Fredlund & Xing, 1994) have been widely used in geotechnical engineering. The van Genuchten model which is simple and has meaningful parameters is used in this study. The van Genuchten equation is written as follows:

$$w = w_r + \frac{(w_s - w_r)}{\left[1 + (\alpha s)^n\right]^m} \tag{2}$$

where w is the actual soil water content at the suction s; w_s and w_r are the saturated water content and the residual water content; α is a parameter related to the air entry suction; m and n are the model parameters with the relationship: $m=1-1/n$.

The fitting curves of M4.0 and M15.3 are also plotted in Figure 2, which shows the van Genuchten model fits well with the measured values for both studied materials. The parameters of van Genuchten model are summarized in Table 2.

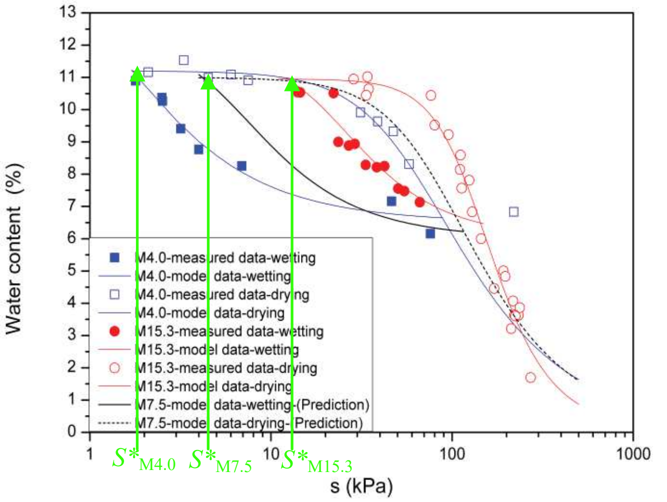

Figure 2. Matric suction obtained by filter paper method as well as model prediction (M4.0, M7.5 and M15.3).

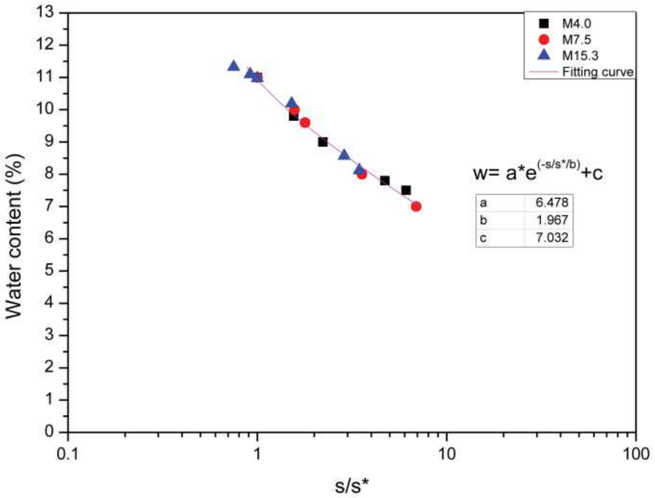

Figure 3. Evolution of water content, as a function of *s/s**.

Table 2. Parameters of van Genuchten model.

Parameters of VG model	M4.0		M15.3		M7.5 (Prediction)	
	Wetting	Drying	Wetting	Drying	Wetting	Drying
α	0.803	0.016	0.049	0.007	0.180	0.012
n	1.929	1.947	2.261	3.025	2.100	2.100
m	0.482	0.486	0.558	0.669	0.524	0.524
w_s (%)	14.3	11.2	11.8	11.0	12.3	11.0
w_r (%)	6.5	0.1	6.0	0.1	6.0	0.1
s^* (kPa)	1.8±0.18		12±1.2		4.2±0.42	

In Figure 2, the s^* value is defined as the suction value corresponding to the intersection point of wetting and drying paths, which is significantly related to fine content. Besides, since the s^* value is very sensible to any variation of the model parameters, this value is presented in Table 2 in a range of between 90%•s^* and 110%•s^* for the lower bound and the upper bound of s^* respectively. Table 2 summarizes the s^* values for M4.0 and M15.3.

Based on the parameters of van Genuchten model of M4.0 and M15.3, the model parameters and the s^* values are predicted for M7.5 presented in Table 2. Figure 2 also shows the prediction SWRC for M7.5 both wetting and drying paths.

Figure 3 shows the evolution of water content, as a function of s/s^*. It can be observed that a simple exponential function could represent the relationship between s/s^* value and water content, which is defined as:

$$w = a \cdot e^{(-s/s^*/b)} + c \tag{3}$$

where a, b and c are constant. In other words, the soil water retention curves for three different materials coincide together by using s/s^* value instead of suction value.

3 REPEATED LOAD TRIAXIAL TESTS (RLTT)

RLTT is widely used to investigate the mechanical behaviours of granular materials. It can simulate the variation of pavement loading conditions to describe the resilient strain behaviours or permanent strain behaviours.

3.1 *Principle of RLTT*

For triaxial tests, the mean normal stress p and the deviatoric stress q are usually used to describe the stress state of samples, which are defined as:

$$p = \frac{\sigma_1 + 2\sigma_3}{3} \tag{4}$$

$$q = \sigma_1 - \sigma_3 \tag{5}$$

where σ_1 is the vertical stress (kPa); σ_3 is the confining pressure (kPa).

The volumetric strain ε_v and the deviatoric strain ε_q are used to describe strain behaviours of samples, which are defined as:

$$\varepsilon_v = \varepsilon_1 + 2\varepsilon_3 \tag{6}$$

$$\varepsilon_q = \frac{2(\varepsilon_1 - \varepsilon_3)}{3} \tag{7}$$

where ε_1 is the axial strain; ε_3 is the radial strain.

As shown in Figure 4, in RLTT, the axial cyclic deviatoric stress q and the cyclic cell pressure σ_3 are applied to samples in phase in each cycle. The axial and radial strain behaviour separates two parts: permanent strain and reversible strain.

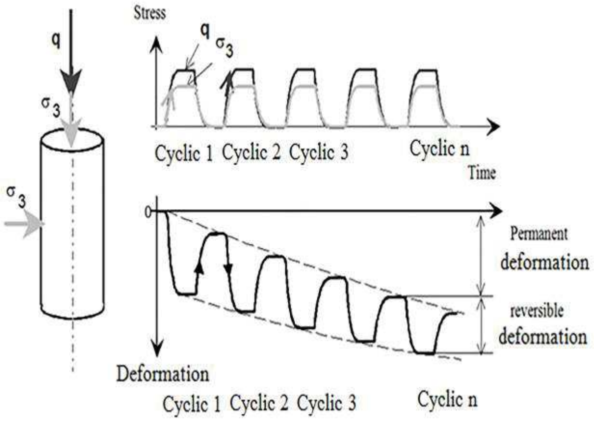

Figure 4. Principle of repeated load triaxial test.

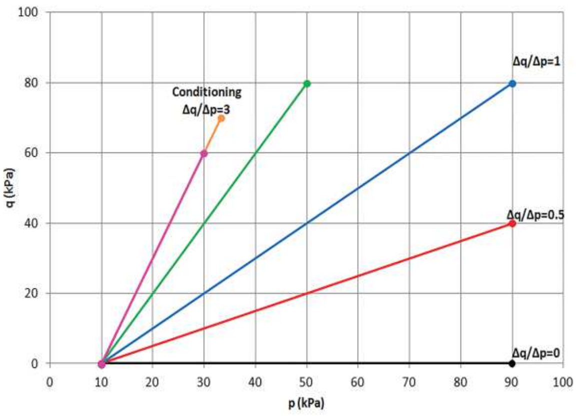

Figure 5. Resilient strain behaviour: stress paths applied.

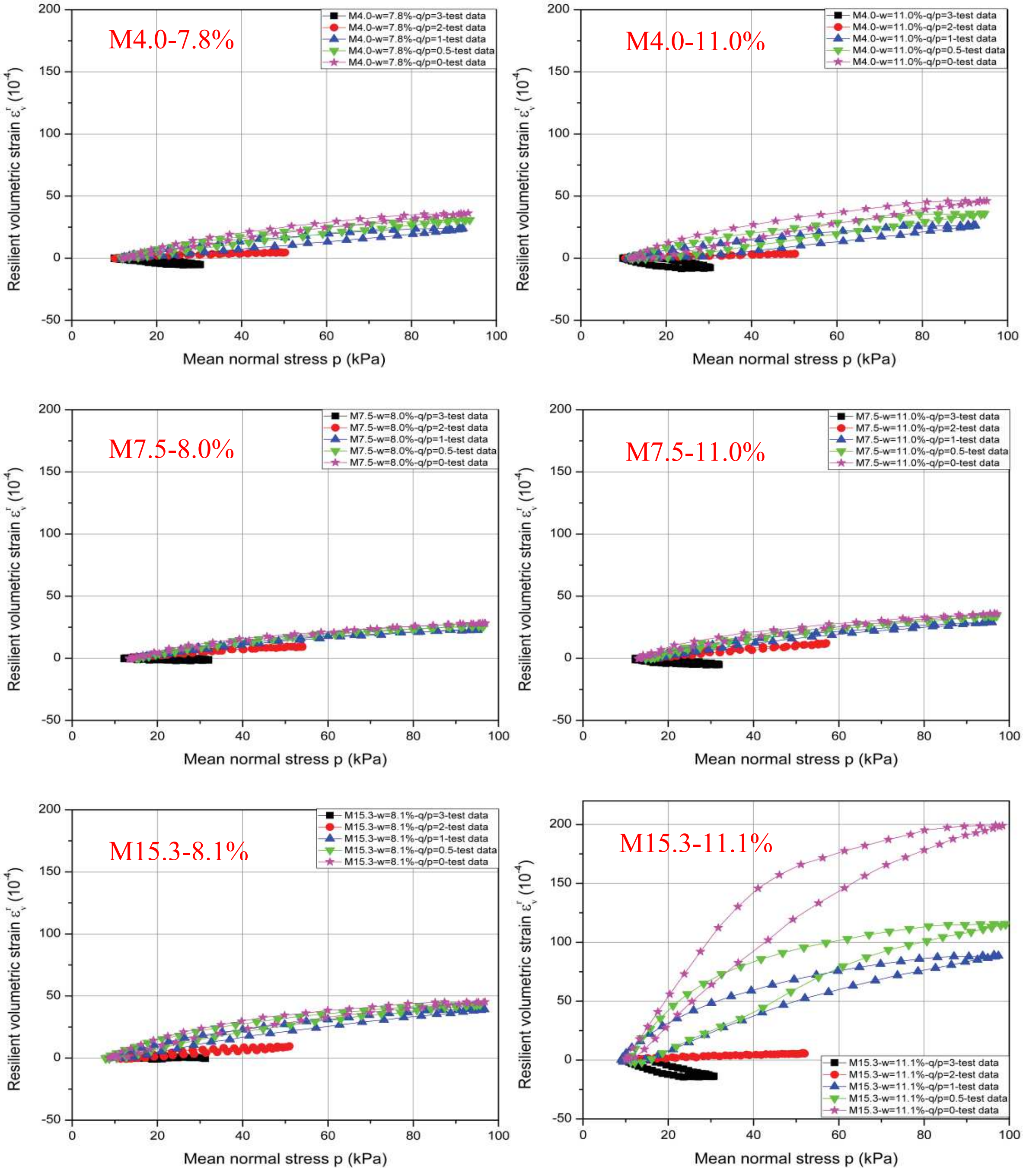

Figure 6. Evolution of resilient volumetric strain $\varepsilon_v{}^r$

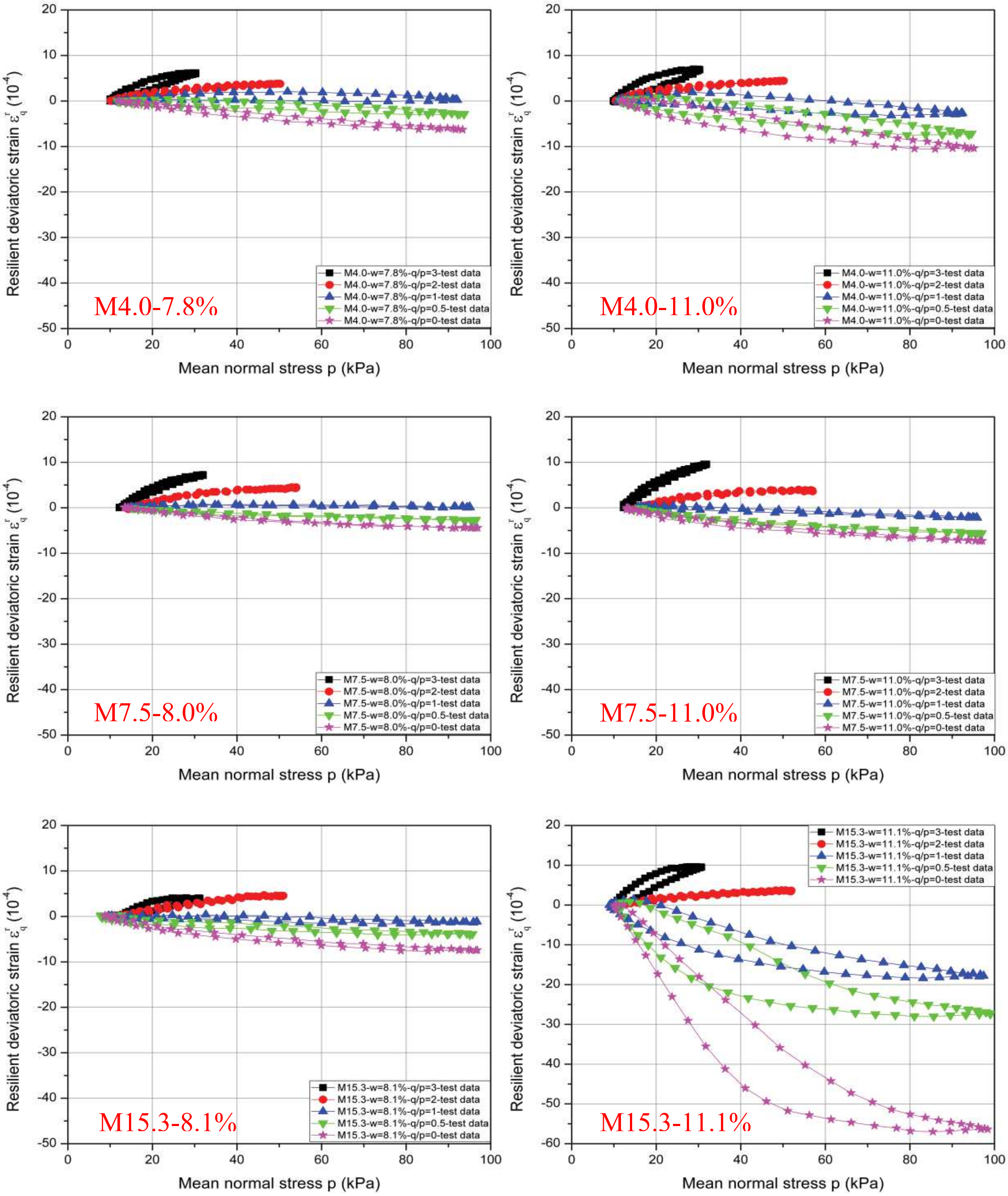

Figure 7. Evolution of resilient deviatoric strain $\varepsilon_q{}^r$

For a given relatively low stress state, without failure, the plastic strain will not increase with increase of number of cycles after enough loading cycles. Then the reversible strain could be treat as resilient strain.

3.2 *Resilient strain tests*

In this study, the repeated triaxial tests are performed with three Missillac sands (M4.0, sand M7.5 and M15.3) for the water contents ranging from 7% to 11% with the same dry density of 2±0.06 g/cm^3. The samples are prepared at a diameter of 150 mm (160 mm for M7.5) and a height of 285±5 mm (320±5 mm for M7.5).

The samples are first subjected to a conditioning phase that consisted of 10^4 loading/unloading cycles to stabilize the plastic strains. At the end of the conditioning phase, the increase in axial plastic strain was lower than 10^{-7} per cycle confirming the stabilized plastic deformation.

After the conditioning phase, 5 different stress paths ($\Delta q/\Delta p$ = 0; 0.5; 1; 2; 3) are applied to each sample. For each stress path, the last cycle of 100 loading/unloading cycles are used to determine the resilient strain behaviours.

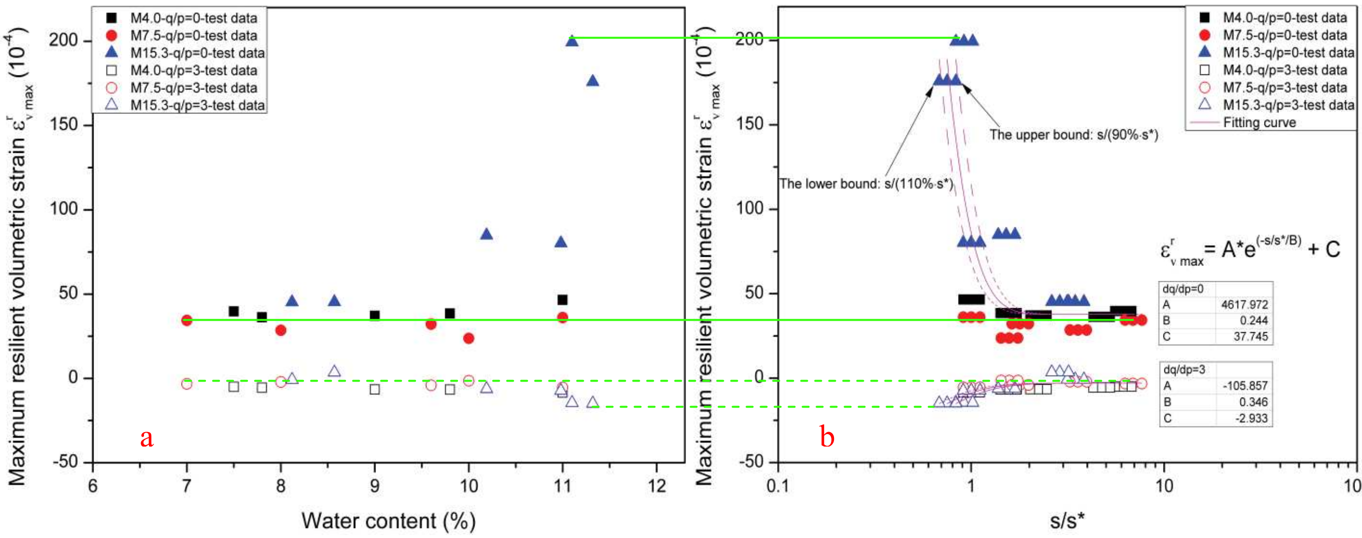

Figure 8. Relationship between maximum resilient volumetric strain $\varepsilon_v{}^r{}_{max}$ and water content w and *s/s** value.

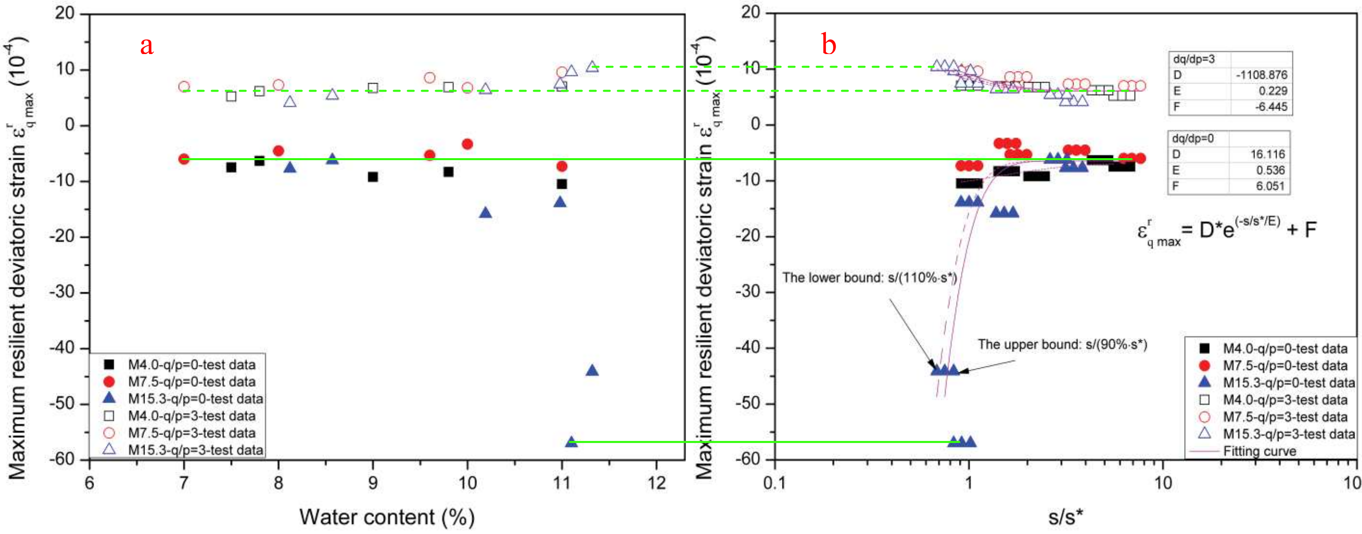

Figure 9. Relationship between maximum resilient deviatoric strain $\varepsilon_q{}^r{}_{max}$ and water content w and *s/s** value

4 TEST RESULTS AND ANALYSIS

4.1 *Resilient strain behaviours*

Figure 6 and Figure 7 present respectively the evolution of resilient volumetric strain $\varepsilon_v{}^r$ and the resilient deviatoric strain $\varepsilon_q{}^r$ in the last cycle for three different Missillac sands (M4.0, M7.5 and M15.3) at two different water contents (8% and 11%). Based on these figures, it can be stated that $\varepsilon_v{}^r$ is positive in the stress paths of $\Delta q/\Delta p$ = 0; 0.5; 1 and 2 (Contraction) while $\varepsilon_v{}^r$ is negative in the stress paths of $\Delta q/\Delta p$ = 3 (Dilation). The resilient deviatoric strain are positive in the stress paths of $\Delta q/\Delta p$ = 2 and 3 and negative in the other stress paths.

Besides, the effect of water content on resilient strain behaviours is obvious: Higher the water content, higher the $\varepsilon_v{}^r$ in each stress path for each material. Higher the water content, higher the $\varepsilon_q{}^r$ in each stress path for each material. For M15.3 material, there are large increases of $\varepsilon_v{}^r$ and $\varepsilon_q{}^r$ with an increase of water content from 8% to 11%, especially for the stress paths of $\Delta q/\Delta p$ = 0; 0.5 and 1. The effect of fine content on resilient strain behaviours is not significant when the fine content increases from 4% to 7.5%. At the same time, a large open loops can be observed for M15.3 at the stress paths of $\Delta q/\Delta p$ = 0; 0.5; 1 and 3.

4.2 *Effect of suction*

In section 2.2, we defined a new parameter *s** which is the suction value of the intersection point of wetting and drying paths in SWRC.

Figure 8 compares the maximum resilient volumetric strain $\varepsilon_v{}^r{}_{max}$ in the last cycle of resilient strain test as a function of water content (Figure 8a) and *s/s** value (Figure 8b) for three materials (M4.0, M7.5 and M15.3) having a water content range of 7% to 11.3% in stress paths of $\Delta q/\Delta p$ = 0 and 3.

As shown in Figure 8a, the $\varepsilon_v{}^r{}_{max}$ increases with the increase of water content (even the results of M7.5 are somehow scatter) like it has been described in Figure 6. Besides, the effect of fine content is important as well as water content: the $\varepsilon_v{}^r{}_{max}$

is different with different fine content and same water content.

In Figure 8b, all of $\varepsilon_v{}^r{}_{max}$ values are plotted in *s/s** plane. The lower bound of *s*/110%•*s** and the upper bound of *s*/90%•*s** are also illustrated in this figure to take into account the sensitivity to variation of the parameters of van Genuchten model. From this figure, it can be stated that a simple exponential function could represent the relationship between all of the $\varepsilon_v{}^r{}_{max}$ values and *s/s** values, which is defined as:

$$\varepsilon^{r}_{v\max} = A\cdot e^{(-s/s^{*}/B)} + C \tag{8}$$

where *A*, *B* and *C* are constant as shown in Figure 8b. As a result, the $\varepsilon_v{}^r{}_{max}$ could be determined by *s/s** only. These results are useful to understand problem of dual variation of the maximum resilient volumetric strain $\varepsilon_v{}^r{}_{max}$ with the water content and the fine content.

As $\varepsilon_v{}^r{}_{max}$, the maximum resilient deviatoric strain $\varepsilon_q{}^r{}_{max}$ are also plotted in water content plane (Figure 9a) and *s/s** plane (Figure 9b) respectively for three different materials (M4.0, M7.5 and M15.3) having a water content range of 7% to 11.3% in stress paths of $\Delta q/\Delta p = 0$ and 3.

In Figure 9a, the $\varepsilon_q{}^r{}_{max}$ increases with the increase of water content and the fine content also plays an important role.

In Figure 9b, another simple exponential function can be observed to represent the relationship between all of the $\varepsilon_q{}^r{}_{max}$ values and *s/s** values, which is defined as:

$$\varepsilon^{r}_{q\max} = D\cdot e^{(-s/s^{*}/E)} + F \tag{9}$$

where *D*, *E* and *F* are constant as shown in Figure 9b.

5 CONCLUSIONS

In this paper, we address the problem of variation of unsaturated state with different fine contents on resilient strain behaviours of a granular material in low-traffic pavements.

The RLTT experimental results in *s/s** plane show that there are two simple exponential functions could represent respectively the relationship between $\varepsilon_v{}^r{}_{max}$ and $\varepsilon_q{}^r{}_{max}$ and *s/s**. Hence, the maximum resilient strain behaviours of this unsaturated granular material in low-traffic pavements could be predicted only by SWRC of each material. These findings are helpful for an easier interpretation of the results and reducing the number of tests required to predict the unsaturated resilient strain behaviours of missillac sand.

Besides, the SWRCs for three different materials locate together as a unique curve in *s/s** plane. This is another new point, and it will be continued in the future studies.

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