Experimental study of resilient modulus of unsaturated soil at different temperatures

Etude expérimentale du module de résilience d'un sol non saturé à différentes températures

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ABSTRACT: Fatigue cracking and failure in asphalt and concrete layer of a road pavement are of great concerns to pavement designers and users. The deformation of this layer is related to resilient modulus (M_R) of subgrade soil under cyclic traffic loads. In the field, subgrade soil is subjected to daily and seasonal variations of soil suction and temperature. Although thermo-hydro-mechanical behaviour of soil has attracted intense attention, suction and thermal effects on M_R under cyclic loading-unloading have rarely been reported. In this study, three series of cyclic triaxial tests have been carried out to investigate MR of an unsaturated silt at different temperatures in a newly developed suction and temperature controlled cyclic triaxial apparatus. The new apparatus is employed to investigate MR of the unsaturated silt at six different suctions (0, 30, 60, 100, 150 and 250 kPa) and two different temperatures (20 and 40 □). To enhance the accuracy of strain measurements, Hall-effect transducers are adopted to measure the local axial and radial deformations of each specimen. The influence of suction and temperature on M_R are presented and discussed.

RÉSUMÉ : Fissuration et rupture par fatigue dans la couche d'asphalte et de béton de la chaussée sont des grandes préoccupations pour les concepteurs et les utilisateurs des chaussées. La déformation de cette couche est liée au module de résilience (M_R) du sol de fondation sous charges cycliques du trafic. Le sol de fondation est soumis à des variations quotidiennes et saisonnières de la succion et de la température sur le terrain. Bien que le comportement thermo-hydro-mécanique du sol ait intensément attiré l'attention, les effets de la succion et de la température sur M_R sous cycles de charge-décharge ont été peu étudiés. Dans cette étude, trois séries d'essais triaxiaux cycliques sont réalisés pour étudier le MR d'un limon non saturé à différentes températures dans un nouvel appareil de test triaxial cyclique à succion et température contrôlées. Le nouvel appareil est utilisé pour étudier le MR du limon non saturé à six succions différentes (0, 30, 60, 100, 150 et 250 kPa) et à ux températures différentes (20 et 40 °C). Afin d'améliorer la précision des mesures de contrainte, des transducteurs à effet Hall sont adoptées pour mesurer les déformations axiales et radiales locales de chaque échantillon. L'influence de la succion et de la température sur les M_R est présentée et interprétée.

KEYWORDS: Unsaturated subgrade soil, resilient modulus, cyclic, suction, thermo-hydro-mechanical

1 INTRODUCTION

Fatigue deformation, cracking and failure in asphalt and concrete layer of any road pavement are of great concerns to pavement designers and users. Their incidence may be caused by many reasons such as increase in traffic volume, deterioration of asphalt and concrete, rutting of unbound granular materials and differential settlement of subgrade soils (Brown, 1997). According to Seed (1962), resilient modulus (M_R), is defined as the ratio of repeated deviator stress to axial recoverable strain in cyclic triaxial test. This ratio is widely used as a stiffness parameter to determine soil deformation under cyclic traffic loads in pavement engineering (Brown, 1997).

In the field, unsaturated subgrade soil is subjected to daily and seasonal variations of pore water pressure (or soil suction) and temperature (Jin et al., 1994). It is generally recognized that the behaviour of unsaturated soil is governed by two stress state variables, namely net normal stress (σ- u_a) and matric suction (u_a -u_w), where σ, u_a and u_w are total normal stress, pore air pressure and pore water pressure, respectively (Coleman, 1962). By controlling these two stress state variables in cyclic triaxial test, Yang et al. (2008) and Ng et al. (2012) observed that M_R increases with an increase in suction but at a reducing rate. Although matric suction is very important for understanding M_R of subgrade soil, it is rarely controlled or measured in resilient modulus tests. This is possibly due to some complexities and difficulties in suction control and measurement. Moreover, suction-controlled tests on unsaturated soil are generally time-consuming and so they are not very welcome by many engineers and researchers.

On the other hand, thermo-hydro-mechanical behaviour of soil has attracted intense attention because of its importance in the field of geo-environmental engineering and energy foundation. Previous experimental studies have illustrated that temperature significantly affects unsaturated soil behaviour such as swelling pressure, collapse potential, shrinkage property, compressibility, water retention behaviour and shear strength (Romero et al., 2003; Tang et al., 2008; Uchaipichat and Khalili, 2009). One important examples of thermal effect on soil behaviour is that the yielding stress of soil specimen at elevated temperature is lower than that observed at room temperature. As far as the authors are aware, thermal effects on M_R of unsaturated soil under cyclic loading-unloading have rarely been reported.

In this study, the influence of two stress-state variables (matric suction and net stress) and temperature on M_R of unsaturated soil under cyclic loading-unloading was investigated in a newly developed suction and temperature controlled cyclic triaxial apparatus. Effects of the number of load applications were also studied.

2 TESTING APPARATUS AND MEASURING DEVICE

Figure 1 shows the newly developed suction and temperature controlled cyclic triaxial system. It consists of two main parts: a suction controlled triaxial apparatus and a heating system. The suction controlled cyclic triaxial apparatus for testing saturated and unsaturated soils was originally developed by Ng and Yung (2008) using the axis-translation technique. In addition to a conventional pore water pressure transducer installed at the bottom of soil specimen, a mid-plane suction probe can be mounted to negative pore water pressure ; at the mid-height of a specimen. More details are given by Ng and Menzies (2007); Ng and Yung (2008); Ng and Xu (2012) and Ng et al. (2012).

The heating system installed inside the triaxial cell consists of a thermostat, a cylindrical heater with air serving as circulating fluid, two small fans for circulating air and two thermocouples. One thermocouple provides feedback to thermostat for temperature control, while the other one is used to check the uniformity of temperature in the triaxial cell. Compared to other suction and temperature controlled triaxial systems reported in the literature, this new system, perhaps, is the first one which can test cyclic behaviour of soil under different suction and temperatures. In addition, this system is equipped with three pairs of Hall-effect transducers, measuring local axial and radial strains at center portion of each soil specimen. After calibration by a micrometer, the resolution and accuracy of each Hall-effect transducer is about 1 and 3 μm, respectively. For a specimen height of 152 mm adopted in this study, a displacement of 3 μm corresponds to an axial stain of about 0.004%.

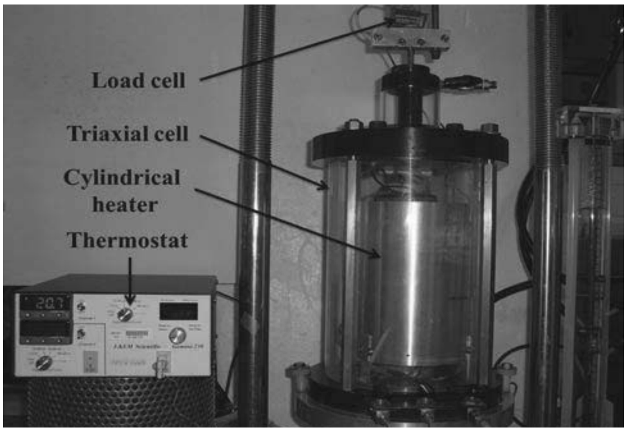

Figure 1. Suction and temperature controlled cyclic triaxial apparatus.

3 SOIL TYPE AND SPECIMEN PREPARATION

The material tested is a completely decomposed tuff (CDT) sampled from Hong Kong. Measured liquid limit, plastic limit and plastic index are 38%, 25% and 13%, respectively. The sand, silt and clay contents are 25%, 71% and 4%, respectively (Ng and Yung, 2008). Following the Unified Soil Classification System, the CDT is described as silt (ML) (ASTM, 2006).

In order to obtain soil specimens with identical fabric, all specimens were prepared following the same method. Each triaxial specimen, 76 mm in diameter and 152 mm in height, is compacted at initial water content of about 16.3% and dry density of about 1760 kg/m^3. In order to produce a uniform specimen, each specimen is compacted in 10 layers. After the completion of compaction, the height and diameter of the specimen are measured by a caliper (readable to 0.01 *mm*) and a PI tape (readable to 0.01 *mm*), respectively. The initial suction of the specimens after compaction is 95±2 kPa as measured by a high capacity suction probe.

4 TEST PROGRAM AND PROCEDURES

Three series of cyclic triaxial tests were performed to investigate effects of (i) net stress and matric suctionand (ii) temperature on M_R of an unsaturated subgrade soil. Figure 2 shows the stress and thermal paths adopted in the three series of tests. The initial state of each specimen is donated by point A in the figure. Firstly, each specimen is isotropically compressed to a net confining stress of 30 kPa (A→E) at room temperature (20 ℃). Depending on the test requriements, specimens are then brought to different suction and temperature conditions at net confining pressure of 30 kPa. Stages of suction equalisation and temperature equalisation are necessary to ensure that the entire specimen reaches the desired suction (u_a -u_w) and temperature conditions.

In Series 1 tests, three specimens W0T20, W30T20 and W60T20 were wetted by decreasing suction from 95 to 0, 30 and 60 kPa (i.e., E→B, E→C and E→D) at 20 ℃, respectively. To investigate suction effects on M_R along the wetting path, M_R of these three specimens were measured and compared In Series 2 tests, three specimens D100T20, D150T20 and D250T20 were dried to suctions of 100, 150 and 250 kPa (i.e., E→F, E→G and E→H) at 20 ℃, respectively. M_R were measured and compared to study suction effects on M_R along the drying path. In Series 3 tests, three specimens W0T40, W30T40 and W60T40 were wetted from 95 to 0, 30 and 60 kPa at 20 ℃ and then heated up from 20 to 40 ℃ at constant suctions (i.e., E→B→B', E→C→C' and E→D→D'). To investigate thermal effect on M_R of unsaturated soil, measured M_R of W0T40, W30T40 and W60T40 was studied and compared with that of W0T20, W30T20 and W60T20 in Series 1. More details of experimental program are summarised in Table 1.

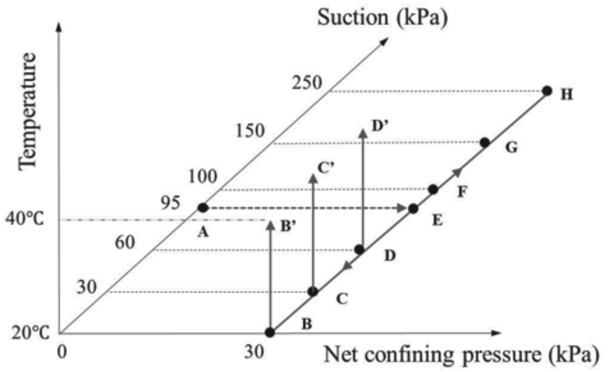

Figure 2. Stress and thermal path of each soil specimen during stages of suction equalisation and temperature equalisation.

Table 1. Details of the experimental program.

Series	Specimen identity	Matric suction (*kPa*)	Temperature (℃)	Equalization time (day)
1-wetting	W0T20	0	20	12
	W30T20	30	20	7
	W60T20	60	20	4
2-drying	D100T20	100	20	4
	D150T20	150	20	7
	D250T20	250	20	13
3-thermal	W0T40	0	40	15
	W30T40	30	40	11
	W60T40	60	40	9

Once a specimen had equalised at a given suction and temperature, it was subjected to cyclic loads to determine its M_R. In each cyclic test, applied axial stress was varied with time following a haversine form while net confining pressure and temperature was maintained constant. For clarity, variations of axial stress during the first and last 10 cycles are shown in Figure 3. The difference between the maximum and minimum axial stresses is defined as cyclic stress q_{cyc}. According to AASHTO (2003) standard for resilient modulus test, four levels of cyclic stress (i.e., 30, 40, 55 and 70 kPa) were considered and applied to each specimen in succession. At each level of q_{cyc}, 100 cycles of loading-unloading at 1 Hz were applied. More details are given by Ng et al., (2012).

In each cyclic triaxial test, constant water content condition is maintained because the dissipation rate of excess pore water pressure is low compared to the rate of repeated traffic loads in the field. The pore water pressure was measured at the base and mid-height of each specimen, as shown in Figure 3. For clarity, only the first and last 10 cycles are shown in the figure. It should be noted that the variations of pore water pressures during the remaining 80 cycles are similar with those in these 20 cycles. It can be seen that pore water pressures measured at the base and mid-height vary with applied deviator stress in similar manner. The magnitude of variation of measured pore water pressure is about 10 kPa at the base and 5 kPa at the mid-height. Previous researchers found that pore water pressure measurement at the mid-height is more representative, since it is not affected by end restraint (Hight, 1982).

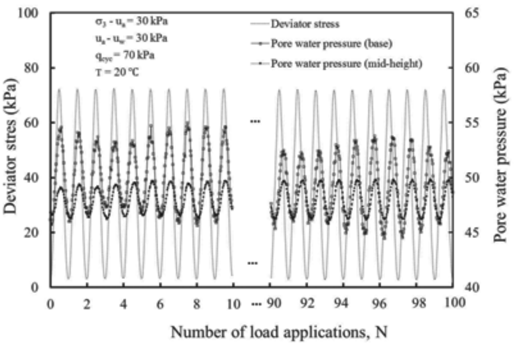

Figure 3. Applied deviator stress and measured pore water pressure during a cyclic triaxial test (modified from Ng et al., 2012).

5 INTERPRETATIONS OF EXPERIMENTAL RESULTS

5.1 Effects of number of load applications (N) on resilient modulus

To investigate the influence of number of load applications on resilient modulus, resilient modulus from the *Nth* cycle (M_r^N) is normalised by resilient modulus from the first cycle (M_r^1). Figure 4 shows the relationship between M_r^N/M_r^1 and N at cyclic stress of 70 kPa, obtained from tests at six different suction (0, 30, 60, 100, 150 and 250 kPa) and two different temperatures (20 and 40 ℃) (see Figure 2 and Table 1). This figure clearly reveals two types of soil response at 20 ℃. At zero matric suction, M_r^N/M_r^1 increases continuously with increasing N (obtained from W0T20). The total increase during the 100 cycles of loading-unloading is up to 20%. This is a consequence of progressive densification resulting from that the application of repeated cyclic stress (Dehlen, 1969; Ng et al., 2012). In this study, contractive volumetric strain of specimen W0T20 measured using Hall-effect transducers is 0.25% at the end of 100 cycles of loading-unloading. The decreasing volume and hence increasing dry density under cyclic loads results in an increase in M_r^N/M_r^1 with increasing N. On the other hand, when matric suction is equal to or larger than 30 kPa (s = 30, 60, 100, 150 and 250 kPa), M_r^N/M_r^1 varies only slightly with N. One reason is that volumetric strain under cyclic loads is much smaller when matric suction is equal to or larger than 30 kPa. For example, measured contractive volumetric strain at suction of 30 kPa is only 0.03%, much smaller than 0.25%. Given such a small volumetric strain as 0.03%, the variation of M_r^N/M_r^1 with N becomes insignificant.

By studying the relationship between normalised M_r^N/M_r^1 and the number of load applications (N), it is evident that measured M_R is sensitive to N values at zero suction but it is almost independent of N values at different suctions.

Considering temperature effects on M_r^N/M_r^1 ratios, it is also revealed in Figure 4 that there is about 5% increase in M_r^N/M_r^1 ratio when temperature increases from 20℃ to 40 ℃. This observation may be explained by thermal effects on the size of yield surface. Romero et al. (2003) reported that the yielding stress of unsaturated soil specimen at elevated temperature is lower than that observed at room temperature, with the same initial void ratio and suction. Given a smaller yielding stress at a higher temperature, it may be expected that the contractive volumetric strain and hence the influence of N on M_r^N/M_r^1 is more significant at a higher temperature.

As also revealed in the figure, the variation of M_r^N/M_r^1 is negligible when N except for the specimen tested at zero suction. A steady resilient modulus was generally achieved within 100 loading-unloading cycles at suctions larger than zero.

5.2 Effects of suction and temperature on resilient modulus

Figure 5 shows the influence of q_{cyc} on measured M_R at different suctions (0, 30, 60, 150 and 250 kPa) and temperature (20 and 40 °C). Reported M_R in the figure is the average resilient modulus of the last five cycles (i.e. N = 96-100). It can bes een from this figure that M_R decrease with an increase in q_{cyc} at all suctions except s = 0. For instance, M_R decrease by about 40% when q_{cyc} increase from 30 kPa to 70 kPa at a suction of 30 kPa and teperature of 20 °C (obtained from W30T20). The observed decrease of M_R with an increase in q_{cyc} is due to the non-linearity of soil stress-strain relationship. Previous studies have demonstrated that soil stiffness is high at small strain but it decays with an increase in strain level (Atkinson, 2000). In the resilient modulus tests, strain level increases with an increase in q_{cyc}, hence measured M_R decreases with an increase in q_{cyc}.

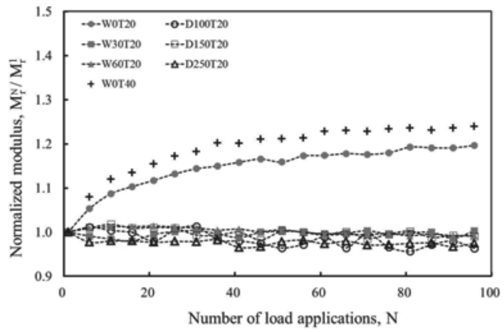

Figure 4. Relationship between normalized resilient modulus and number of load applications at a cyclic stress of 70 kPa (modified from Ng et al., 2012).

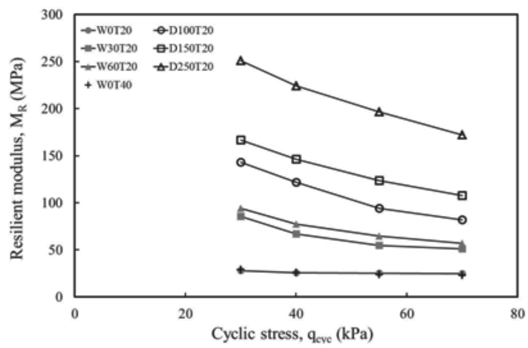

Figure 5. The influence of cyclic stress on resilient modulus at different suction and temperature conditions (modified from Ng et al., 2012).

This figure also reveals that M_R increases with increasing s significantly, irrespective of whether it is along a drying or a wetting path. At cyclic stress of 30 kPa and temperature of 20 ℃, M_R increases by up to one order of magnitude when s increases from 0 to 250 kPa. The beneficial effects of s on M_R arise due to at least two possible reasons. Firstly, when a soil specimen becomes unsaturated, voids are partly filled with water and partly occupied by air, resulting in an air-water interface in each void. When there is an increase in matric suction, the radius of an air-water interface decreases and hence induces a larger normal inter-particle contact force (Mancuso et al., 2002; Wheeler et al., 2003; Ng and Yung, 2008). This normal inter-particle contact force provides a stabilizing effect on an unsaturated soil by inhibiting slippage at particle contacts and enhancing the shear resistance of the unsaturated soil (Wheeler et al., 2003). Secondly, an increase in s induces the shrinkage of soil specimen (Ng and Pang, 2000). Due to the stronger inter-normal force between particles and higher density, M_R measured during cyclic loading-unloading is larger at higher suctions. Further inspection of this figure reveals that the relationship between M_R and s is nonlinear along a wetting path, along which soil suction is smaller than initial suction. Given the same increase in s, the percentage of increase in M_R is much larger in the lower suction range. At a cyclic stress of 30 kPa, M_R doubles when s increases from 0 to 30 kPa, while only increases by 10% when s increases from 30 to 60 kPa. Along a drying path, the increase rate of M_R with increasing s is almost constant. The different results observed in different suction ranges are likely related with AEV of a soil specimen. The different results observed in different suction ranges are probably because the bulk water effects dominate soil behaviour when matric suction is lower than AEV of soil specimen (here about 60 kPa) and meniscus water effects dominate soil behaviour when matric suction exceeds AEV (Ng and Yung, 2008).

Comparing average steady state values of M_R measured at the last 5 cycles at zero suction but at two different temperatures shown in Figure 5, average M_R measured at 20 ℃ (W0T20) is almost identical to that measured at 40 ℃ (obtained W0T40). At the four levels of cyclic stress, the maximum difference in M_R at 20 ℃ and at 40 ℃ is about 7%. In the temperature ranges studied, the thermal effect may be considered to be negligible at zero suction. This negligible thermal effect at zero suction on M_R seems to be in agreement with previous experimental evidence. Romero et al. (2003) and Uchaipichat and Khalili (2009) observed from their oedometer tests that soil stiffness during unloading seems to be independent of thermal conditions. To fully understand the thermo-hydro-mechanical effects on M_R, further experimental and theoretical studies at different suction values under different temperature conditions are needed.

6 SUMMARY AND CONCLUSIONS

Three series of cyclic triaxial tests have been carried out to investigate M_R of an unsaturated silt at different temperatures in a newly developed suction and temperature controlled cyclic triaxial apparatus.

By studying the relationship between normalised M_r^N/M_r^1 and the number of load applications (N), it is evident that measured M_R is sensitive to N values at zero suction but it is almost insensitive to N at different suctions. At zero suction, M_R measured at cyclic stress of 70 kPa increases with N by about 20% during 100 cycles of loading-unloading. When suction is equal and larger than 30 kPa, M_R measured at the same cyclic stress is almost independent of N. For unsaturated CDT specimens tested, a steady resilient response was achieved within 100 cycles of loading-unloading.

For a given stress level the increase of M_r^N/M_r^1 with increasing N is more significant at higher temperature at zero suction. This observation may be explained by the fact that yielding stress of soil specimen is smaller at higher temperature.

Measured M_R is found to be dependent on cyclic stress level and suction value. It decreases with cyclic stress because soil stress-strain behaviour under cyclic loads is highly non-linear. On the other hand, M_R increases significantly with suction. When suction increases from 0 to 250 kPa, M_R increases by up to one order of magnitude. This is attributed to suction induced additional inter-particle normal force which stiffens soil specimen.

It is clear that more theoretical and experimental work are needed to understand unsaturated cyclic soil behaviour and engineering properties under different suction and temperature conditions.

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