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Laboratory and Theoretical Investigations on Mechanical Behavior of PLFG Mixture

[1]Wang Wei, [2]Lu Tinghao, [1]Jin Weimin and [1,3]Chi Xuchao
[1]School of Engineering, Shaoxing University, Shaoxing, 312000, China
[2]Geotechnical Institute, Hohai University, Nanjing, 210098, China
[3]Melbourne School of Design, Melbourne University, Victoria, 3010, Australia

Abstract: Phosphogypsum-lime-flyash-gravel Mixture (PLFG) is usually used to strengthen road foundation of geotechnical engineering. It is important to correctly understand its mechanical behavior before corresponding design. In this present paper, compaction test, one-dimensional compression test and dry-shrinkage test were conducted to determine optimum mixture ration of PLFG. compression test on PLFG with optimum ration was carried out in order to investigate its stress-strain curve. Experiment data show that PLFG is with high bearing capacity and good stiffness. A new composite-exponent model was established, which is available for both hardening and softening type strain-stress curves of PLFG. Mathematical behavior of the presented model is far better than others to describe PLFG's structural property. Finally, comparison between PLFG tested data and new model simulation was performed and good agreements have been found. This research is helpful for engineering sustainable utilization of to bring economy and to reduce environmental pollution.

Key words: Phosphogypsum, PLFG, laboratory test, stress-strain curve, composite-exponent model

INTRODUCTION

Increasing amounts of residues and waste materials coming from industrial activities in different processes have become an increasingly urgent problem for the future. Phosphogypsum (PG) is one kind of these waste materials. PG is a waste by-product of phosphoric acid production, which is usually disposed in the environment because of its restricted use in industrial applications (Singh, 2000). One ton phosphoric acid production usually creates five tons PG. It is reported that annually production amount of PG is more than 1000 million ton all over the word and just 4% of them is reutilized. In China, there is about 10 million ton PG produced annually by chemical factory (Xu *et al*., 2006; Zhao *et al*., 2009). So, many PG may occupy an area ranging from several acres to hundreds acres near the factory and pose a serious problem of disposal and health hazards in the country.

At the same time, there are many structures built in soft soil area, such as express way embankment, air port, as well as many factory plants. The best known geotechnical disadvantages of soft soil are its low mechanical properties and poor resistance to settlement. Due to the presence of impurities of phosphates and organic matter, PG finds limited scope for use in the production of cement, fertilizer, building materials, etc. However, PG can be extensively used as stabilization material to improve or replace soft soil and to reduce its disadvantages at least partially (Li and Lu, 2003; Zhao and Shi, 2007; Degirmenci, 2008). This method can well cope with two problems, namely utilization of PG and stabilization of soft soil foundation. In practice, in order to make good use of PG, lime, fly ash and gravel are always mixed together with it to form Phosphogypsum-lime-flyash-gravel Mixture (PLFG) reinforced foundation supporting above structures (Degirmenci *et al*., 2007; Degirmenci, 2008).

Before corresponding engineering design, it is of great importance to correctly understand geotechnical mechanical behavior of PG mixture, especially deviator Stress-axial Strain Curve (SSC) under complex stress conditions. Many experimental and theoretical studies have been devoted to this subject (Papanicolaou *et al*., 2009; Yang *et al*., 2009). Experiments on frozen-thawed deformation, flexural strength, softening in water, dry-shrinkage and unit weight values of PG-fly ash or PG-lime mixtures were conducted by Xu *et al*. (2006) and Degirmenci (2008) but compressive strength experiments with various mixing ratios of PLFG were not, at least not enough, performed. On the other hand, although hyperbolic function model and exponent function model were proposed to describe compressive SSC of PLFG, these two conventional models have some limitation that they are available to only hardening type curves but softening curves (Wang *et al*., 2007).

Corresponding Author: Wang Wei, School of Engineering, Shaoxing University, Shaoxing, 312000, China

In this present study, laboratory experiments with triaxial compression apparatus on PLFG were carried out in consideration different mixing ratios and its SSC was investigated from both experimental and theoretical aspects. This research puts good foundation for engineering sustainable utilization of PG, especially as road foundation material, to bring economy and to reduce environmental pollution.

BASIC LABORATORY TESTS ON PLFG

Experiment materials: These experiments were carried out at Hohai University, China. PG, gravel, fly ash and lime of this experiment were supported by corresponding factories at Suqian city, Jiangsu. Mass percents of gravel with 0-5, 5-10 and 10-20 mm diameter size are 30, 34, 36%, respectively. Original components in mass of other three materials are listed in Table 1.

According to many trial tests and engineering investigation, two typical mixture ratios in mass of used PLFG are determined as good mixtures to conduct further mechanical test including compaction test, one-dimensional compression test, dry-shrinkage test and triaxial compression test. Their mixing ratios in mass are listed in Table 2.

Compaction test: In order to study maximum dry density of No. 1 and No. 2 PLFG mixtures, heavy compaction test were conducted with different water contents. Investigated curves between water content and maximum dry density are shown as in Fig. 1. This figure shows that optimum water contents of No.1 and No. 2 PLFG mixtures are both about 6%. However, maximum dry density of No. 2 is much bigger than that of No. 1. From this point, No. 1 PLFG mixture has good compaction behavior.

One-dimensional compression test: Objective of this test is to understand future stiffness and resilience modulus of PLFG as road foundation materials. Because size of conventional one-dimensional compression apparatus is very small to PLFG particles, diameter of used apparatus is improved form 6.18-10.00 mm. This test experienced more than one month with cyclic compressing loading. From the investigated data, we can draw following conclusions: (1) Compressing deformation of No. 1 and No. 2 PLFG mixtures are very small; (2) They both exhibit elastic behaviour with cyclic loading after first loading cycle. Above conclusions give rise that both No. 1 and No. 2 PLFG mixtures have good stiffness and resilience modulus as road foundation materials under cyclic compressing loading.

Table 1: Original component of used PLFG materials (%)

Kinds	PG	Fly Ash	Lime
CaO	26.58	4.03	82.65
SiO_2	3.03	35.98	0.30
MgO	0.29	0.72	1.52
Al_2O_3	1.00	24.24	/
Fe_2O_3	0.95	8.41	/
Na_2O	0.39	6.30	/
SO_3	40.26	/	0.91
Crystal H_2O	17.11	/	/
P_2O_5	2.55	/	/
Others	8.37	20.16	1.80

Table 2: Two typical mixture ratios in mass of used PLFG (%)

No.	Gravel	PG	Fly ash	Lime
1	90	8.5	1	0.5
2	90	8.0	1	1.0

Dry-shrinkage test: For road foundation materials, it should have enough dry-shrinkage property and crack-proof resistance because it is exposed to nature all day and all night. So dry-shrinkage test is a must to PLFG. Dry-shrinkage cyclic loading were simulated and conducted experiencing 3 months. The finally dry-shrinkage specimens indicate that PLFG mixtures have no any crack and have good dry-shrinkage stability.

TRIAXIAL COMPRESSION TEST ON PLFG

Triaxial compression test: According to investigations of previous compaction test, one-dimensional compression

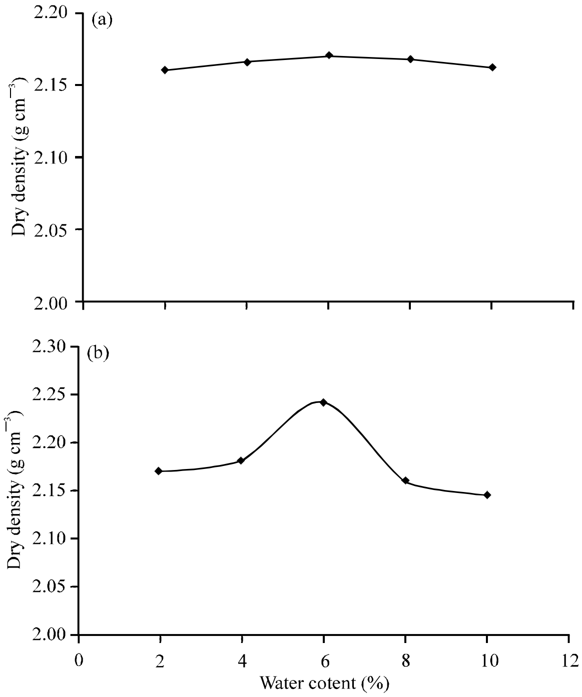

Fig. 1(a-b): Water content and maximum dry density, (a) No. 1 PLFG and (b) No. 2 PLFG

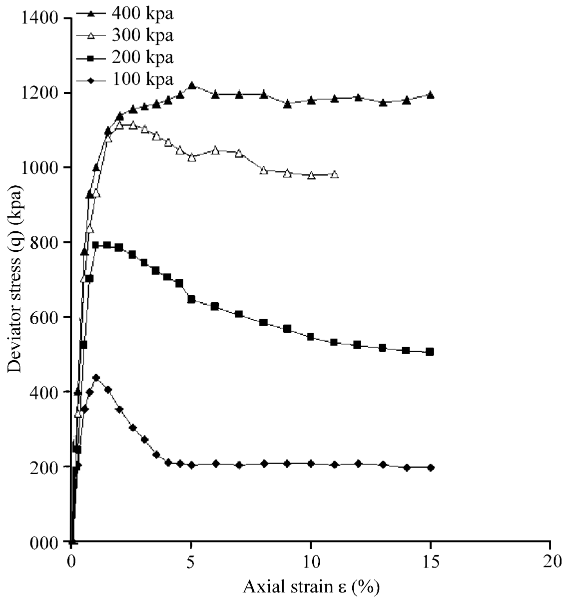

Fig. 2: Investigated stress-strain data of No. 1 PLFG

test and dry-shrinkage test, although two typical PLFG mixtures have good mechanical behavior, No. 1 is better than No. 2 as road foundation materials.

In fact, road foundation is always under 3-dimensional stress state, so it is necessary to study its behavior by using triaxial compression apparatus. The compression experiments were conducted using conventional triaxial compression apparatus under unstauration, unconsolidation, undrainage condition. The No. 1 PLFG mixture was prepared as column samples to test with 61.8 mm diameter and 125 mm height. Four different confining water pressures, namely minor principal stress σ_3, are loaded as 100, 200, 300 and 400 kpa.

Test data analysis: SSC with various confining stress of No. 1 series were investigated and plotted in Fig. 2. In this figure, ε denotes axial strain and q denotes deviator stress, namely difference between major principal stress σ_1 and minor principal stress σ_3, $q = (\sigma_1 - \sigma_3)$.

Figure 2 gives rise to following conclusions. SSC of PLFG appear hardening behavior with big $\sigma_3 = 400$ kpa but it appear obvious softening behavior with small $\sigma_3 = 100$ kpa. It should be noted that this is different from softening property of gravel and hardening property of PG and fly ash (Wu *et al*., 2007), which deserves enough attention for engineers during engineering design. Peak strength of PLFG with maximum 1200, is much bigger than that of individual PG or gravel, which offers PLFG high bearing capacity to resist heavy load. At same time, all SSCs reach their peak stress with small strain less than 3%, which gives PLFG good stiffness to resist deformation. High bearing capacity and good stiffness enable PLFG with these two mixing ratios as road foundation material.

COMPOSITE-EXPONENT SSC MODEL

New model expression: After experiment investigation, it is necessary to establish a good mathematical model to describe SSC in order to well design or simulate many engineering behaviors of PLFG treated foundation which are critical to management safety of above structures. Total settlement, differential settlement, stress distribution, lateral deformation and stress level are some of them.

Hyperbolic model and exponent function model were proposed to describe hardening SSC of PLFG. Their expressions are:

$$\begin{cases} q = \dfrac{\varepsilon}{1/G(0) + \varepsilon / q(\infty)} \\ q = q(\infty)[1 - e^{-G(0)\varepsilon/q(\infty)}] \end{cases} \tag{1}$$

where, q Eq. 8 and G (0) are two undetermined parameters with meaning of ultimate strength and initial tangent modulus, respectively. These models are extensively used because of their parameters with identical physical meanings. Unfortunately, they can not express softening type SSC of PLFG, which often reduce simulating accuracy of engineering design and lead engineering accident. Good model should well describe both hardening and softening type SSC.

To this point, a composite-exponent model is established by authors, which can be written as:

$$q = (a\varepsilon - b)e^{-c\varepsilon} + b \tag{2}$$

where a, b and c are three undetermined parameters and $a \geq 0$, $b>0$, $c>0$.

Mathematical property with a>0: Taking $\varepsilon = 0$ and $\varepsilon = \infty$ in Eq. 2, we can easily deduce initial value and ultimate strength of the new model:

$$\begin{cases} q(0) = 0 \\ q(\infty) = b + \lim\limits_{\varepsilon \to \infty} \dfrac{a\varepsilon - b}{e^{c\varepsilon}} = b \end{cases} \tag{3}$$

Differentiating Eq. 2 with ε gives its first order derivative, denoted by G, namely tangent modulus:

$$\begin{cases} G = \frac{dq}{d\varepsilon} = e^{-c\varepsilon}(a + bc - ac\varepsilon) \\ G(0) = a + bc \end{cases} \tag{4}$$

where G (0) is initial tangent modulus with $\varepsilon = 0$. Equation 4 shows that G has only one zero point, ε_p. When $\varepsilon<\varepsilon_p$, G is positive and Eq. 2 is monotone increasing with ε. When $\varepsilon<\varepsilon_p$, G is negative and Eq. 2 becomes monotone decreasing with ε. The coordinate, (ε_p, q_p), of only one peak point of the new model can be determined as:

$$\begin{cases} \varepsilon_p = 1/c + b/a \\ q_p = ae^{-(1+bc/a)}/c + b \end{cases} \tag{5}$$

Differentiating Eq. 4 with ε gives second derivative of the complex model:

$$\frac{d^2q}{d\varepsilon^2} = (ac^2\varepsilon - 2ac - bc^2)e^{-c\varepsilon} \tag{6}$$

A conclusion can be drawn from Eq. 6 that second order derivative has only one zero point, ε_i. When $\varepsilon<\varepsilon_i$, second order derivative is negative and Eq. 2 is convex with ε. When $\varepsilon<\varepsilon_i$, first order derivative is positive and Eq. 2 becomes concave with ε. The coordinate, (ε_i, q_i), of only one inflection point of the new model is:

$$\begin{cases} \varepsilon_i = 2/c + b/a \\ q_i = 2ae^{-(2-bc/a)}/c + b \end{cases} \tag{7}$$

Putting Eq. 3, 5 and 7 together, we can get following equation set:

$$\begin{cases} q(0) = 0 \\ q(\infty) = b \\ G(0) = a + b \\ q_p = ae^{-(1+bc/a)}/c + b \\ q_i = 2ae^{-(2-bc/a)}/c + b \end{cases} \tag{8}$$

It can be seen from the above analysis that the new model has the following properties:

- It goes through point (0, 0)
- Its curve is divided into ascending and descending section by peak point (ε_p, q_p)
- There is a inflection point (ε_i, q_i) in the descending section and its curve is convex and then concave after this point
- The curve converges to $q(\infty)$ (8)

These four properties fully reflect the mechanical behaviours of softening model as shown in Fig. 3.

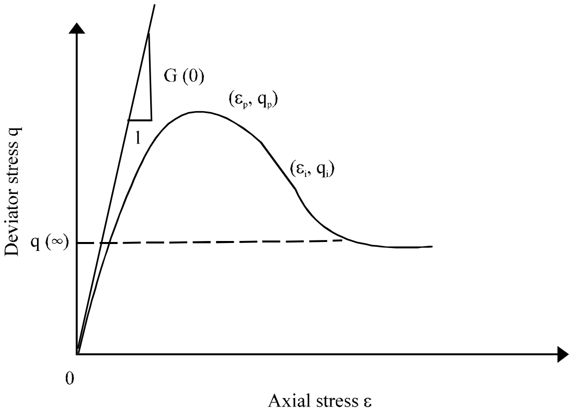

Fig. 3: Mathematical property of new model

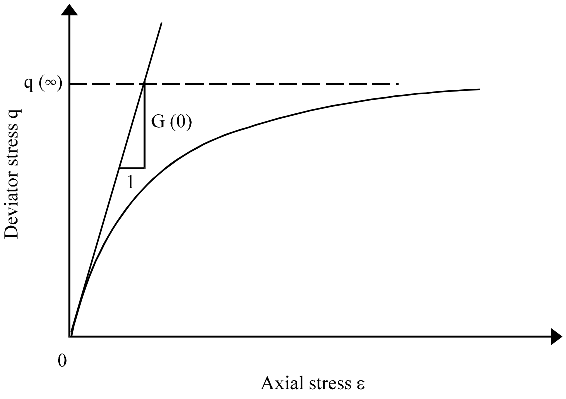

Fig. 4: Mathematical property of new model

Mathematical property with a = 0: Above discussion is assumed that value of parameter a >0. If a = 0, Eq. 2-8. changes into following expression:

$$\begin{cases} q = b - be^{-c\varepsilon} \\ q(0) = 0; q_p = q(\infty) = b \\ G = \frac{dq}{d\varepsilon} = bce^{-c\varepsilon} > 0; \frac{d^2q}{d\varepsilon^2} = -bc^2e^{-c\varepsilon} < 0 \end{cases} \tag{9}$$

It is obvious that the first order derivative is positive which enables new model as monotone increasing function. At the same time, its negative second order derivative ensures its convex shape. Peak strength becomes ultimate strength and infect point disappears. All above properties are well fitted to hardening type SSC appearance, shown as in Fig. 4.

Further study shows that new model, Eq. 2 is eligible to both hardening and softening type SSC of PLFG and has extensive applicability. With constant $q(\infty)$ Eq. 8 and decreasing parameter a, softening property of Eq. 2

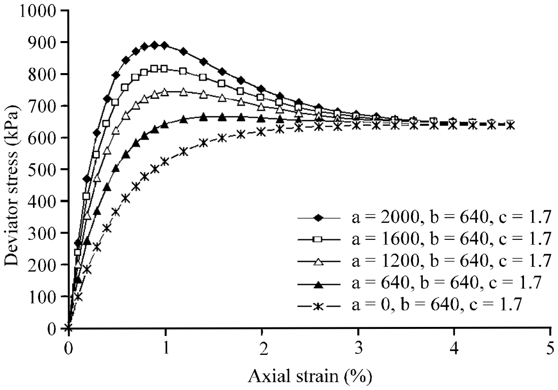

Fig. 5: Application ability for composite model

disappears gradually, shown as in Fig. 5. When a = 0, Eq. 2 becomes equal to exponent function model.

PROCEDURE TO DETERMINE PARAMETERS

Fitted values based tested SSC: Although, new model Eq. 2 has good theoretical and mathematical properties discussed in above section, it should be to carry out enough fitting from tested SSCs with different confined pressures in order to verify its accuracy and practical applicability.

Because absolute values of confined pressures with kpa unit are relative bigger, we convert them with 10^5 pa unit during following fitting which can conveniently reduce the fitting error. Fitted values of parameters are listed in Table 3.

From Table 3, we can obtain that:

- With bigger confined pressure, values of parameter *a* become smaller and smaller from 103226.3-0.002 almost equal to zero. This can be interpreted from Fig. 2 and 5 that the soften behavior of CCS decreases even disappears with bigger confined pressure
- With bigger confined pressure, values of parameter b become bigger and bigger from 208.8-1179.9. This can be interpreted from Eq. 3, 9 and Fig. 2 that the ultimate strength of CCS increases with bigger confined pressure

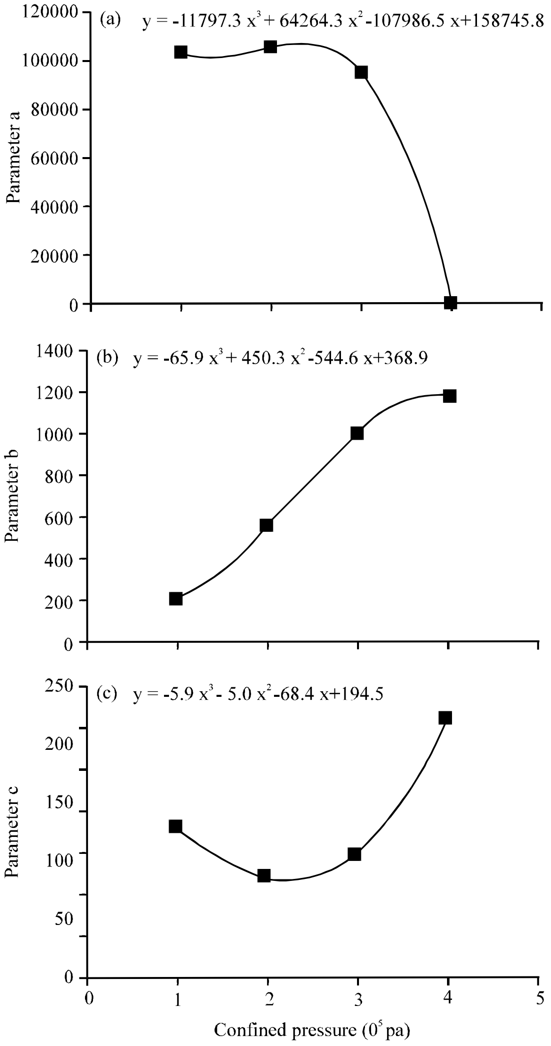

Fig. 6(a-c): Fitted curves of new model parameters, (a) Parameter a, (b) Parameter b and (c) Parameter c

Table 3: Fitted values of three parameters of new model

σ3/(10^5 Pa)	a	b	c
1	103226.300	208.8	127.05
2	105451.500	554.1	85.30
3	94637.400	1009.5	104.90
4	0.002	1179.7	221.50

Simulated function based confined pressures: It is very important to understand relationship between confined pressures and model parameters (a, b, c) before practical numerical simulating and engineering design. From Table 3, this relationship can be obtained, as shown in Fig. 6.

From this figure, parameters (a, b, c) can all be described as three-order power function. Combining Eq. 2 and Fig. 6, generalized SSC model of PLFG can be expressed as:

$$\begin{cases} q = (g_1\varepsilon - g_2)e^{-g_3\varepsilon} + g_2 \\ g_1 = -11797.3\sigma_3^3 + 64264.3\sigma_3^2 \\ \qquad -107986.5\sigma_3 + 158745.8 \\ g_2 = -65.9\sigma_3^3 + 450.3\sigma_3^2 - 544.6\sigma_3 + 368.9 \\ g_3 = 5.9\sigma_3^3 - 5.05.9\sigma_3^2 - 68.4\sigma_3 + 194.5 \end{cases} \tag{10}$$

Generally speaking, Eq. 10 can simulate SSC of PLFG with any confined pressure. Four confined pressures, 50, 150, 250 and 350, are selected and putted into Eq. 10 and the simulated results are shown in Fig. 7. It should be noted that absolute values of these four confined pressures are used as 0.5, 1.5, 2.5 and 3.5 with 10^5 kpa unit in Eq. 10.

MODEL VALIDATION BY TESTED DATA

In order to verify the accuracy of new proposed model, Eq. 2 and 10, four investigated SSCs of PLFG in this experiment are chosen to compare with model simulating results, shown as in Fig. 8.

Comparison shows that simulated results of new model with Eq. 10 are very close to investigated data. However, hyperbolic model and exponent function model with Eq. 1 can not well simulate these SSCs due to lack of softening behavior.

In order to further analyze the accuracy of the new presented model, the definition of the relative difference RD is presented:

$$RD = \frac{q_t - q_s}{q_t} \times 100\% \tag{11}$$

where, in q_t means the tested data and q_s means the simulated data. The relative difference RD of the new presented model is calculated by Eq. 11 and shown as in Fig. 9. Figure 9 indicates that the relative difference of the

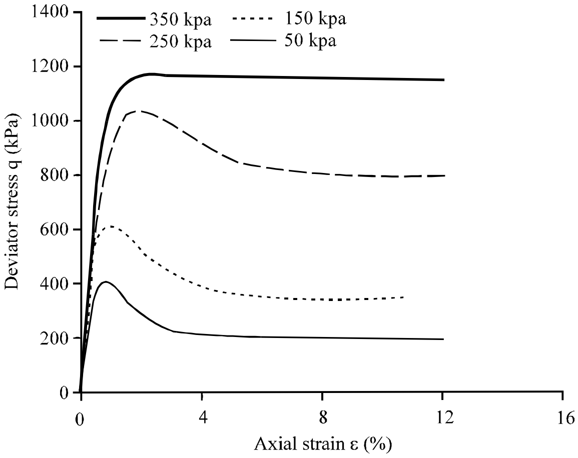

Fig. 7: Simulated and tested stress-strain curves

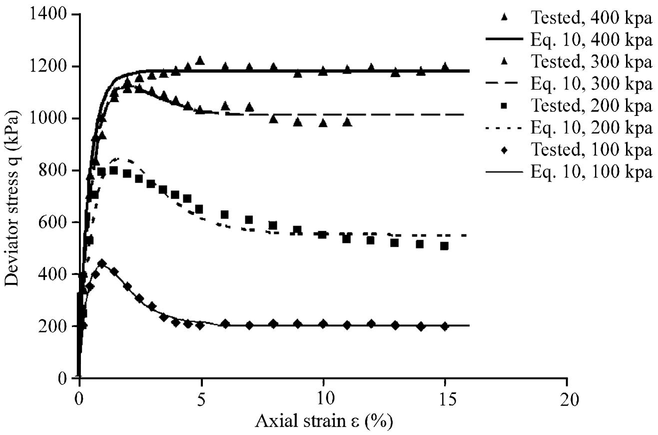

Fig. 8: Simulated and tested stress-strain curves

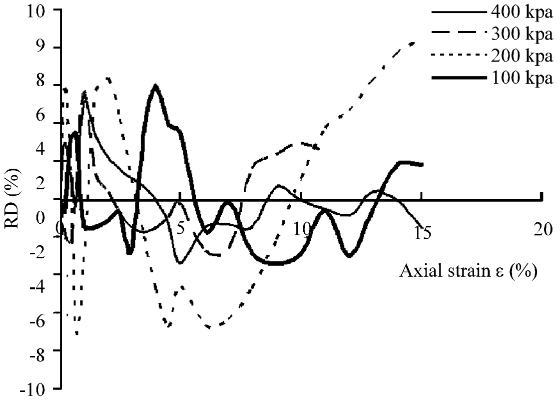

Fig. 9: Relative difference of the presented model

new presented model is very small, which proves the accuracy of the new model from another aspect.

CONCLUSION

Compression mechanical behavior and mathematical model of PLFG were studied in detail from experimental and theoretical aspects. Main results of this study are following:

- Basic laboratory tests on two typical PLFG mixtures were conducted to understand its compaction, one-dimensional compression and dry-shrinkage behaviors. These tests show that, although both two typical PLFG mixtures have good mechanical behavior, No. 1 is better than No. 2 as road foundation materials
- Triaxial compressive tests on No. 1 kind PLFG with were carried out. Its triaxial compressive SSC appears hardening behavior with big confining pressure but it appears obvious softening behavior with small confining pressure, which deserves enough attention for engineers during engineering design
- Higher peak strength and corresponding small strain offers PLFG high bearing capacity to resist heavy load and good stiffness to resist deformation, which enable PLFG as good road foundation material
- New established composite-exponent model is eligible to for both hardening and softening type SSCs of PLFG. Procedure to determine its parameters is presented
- Good agreements have been found between PLFG tested data and new model fittings. Correlation coefficients and relative difference show that new proposed model is perfect

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