EVALUATION OF RESILIENT MODULUS MODELS FOR A HIGH QUALITY CRUSHED STONE

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Abstract

As the traffic volumes have increased in the past several decades, the traditional empirical design methods for road pavements are not sufficiently reliable. The mechanistic-empirical design approach is applied and has been improved in many countries. The Resilient Modulus was regarded as the best input parameter in the mechanistic-empirical design method. Many efforts have been made to investigate the Resilient Modulus of the granular material and lots of models have been proposed and implemented in different materials and conditions. But for particular material such as high quality crushed stone, an appropriate characterization model should be developed. This paper reports on monotonic and cyclic triaxial tests that were carried out on a high quality crushed stone (G1) to investigate the failure strength and resilient response. Classical exponential model, Universal and TU-Delft models are selected and evaluated in term of Resilient Modulus estimation. At the end of this paper a new matrix suction pressure dependant model is presented.

1. INTRODUCTION

Several developments over recent decades have offered an opportunity for more rational and rigorous road pavement design procedures (Regis, 2006). In many of the mechanistic-empirical road pavement design method, the granular material is not characterized extensively. Over the last five decades, many researchers have been investigating the resilient behaviour of granular materials as the input parameter for mechanistic design. The first attempt to observe the resilient properties of unbound granular material was made by Hveem in 1950's (Hveem, 1955). The actual concept of Resilient Modulus was introduced formally by Seed in 1960's (Seed et al, 1962). After that data from many laboratories was obtained in order to model the nonlinear stress dependency of Resilient Modulus and Poison's Ratio. Resilient response of unbound granular materials is usually characterized by Resilient Modulus and Poison's Ratio or by Shear and Bulk Modulus (Lekarp et al, 2000).

In this present paper, some classical models for Resilient Modulus of granular material were reviewed and selected to evaluate the applicability for a high quality crushed stone (G1).

Mr-θ Model

A practical nonlinear description of Resilient Modulus of unbound granular material was reported by Hicks and Monismith (Hicks and Monismith, 1971). In this model the Resilient Modulus was expressed as the function of sum of the principal stress as shown in Equation 1.

$$M_r = \mathbf{k_1} \boldsymbol{\theta}^{\mathbf{k_2}} \qquad \text{(Eq. 1)}$$

Where, θ is the sum of the principal stress (σ_1+2σ_3), kPa;
$\mathbf{k_1}$ and $\mathbf{k_2}$ are regression constants.

However, this model has some drawbacks (Hicks and Monismith, 1971; Uzan, 1985). Uzan identified a shortcoming of M_r-θ model in 1988. He pointed out this model fails to account for the effects of shear stress on the Resilient Modulus and is therefore applicable in a small range of stress paths. It also fails to present the effect of different combination of σ_1 and σ_3. It is obvious that different combinations can result in different resilient properties. So this model has some limitations for modelling of the Resilient Modulus even though it is simpler and more easily applied in Finite Element Modelling.

Uzan Model

Uzan proposed a modified M_r-θ model in 1985. The model is defined as Equation 2.

$$M_r = \mathbf{k_1} \boldsymbol{\theta}^{\mathbf{k_2}} \boldsymbol{\sigma_d}^{\mathbf{k_3}} \qquad \text{(Eq. 2)}$$

Where, σ_d is deviator stress ($\sigma_1 - \sigma_3$), kPa; $\mathbf{k_1}$, $\mathbf{k_2}$ and $\mathbf{k_3}$ are regression constants.

The Uzan model seems to account for shear and dilation effects more adequately and thereby fitting the test data better than the M_r-θ model.

TUD (Delft University of Technology) Model

From extensive laboratory tests of the sub-base sands, Huurman has proposed a model, expressing as Equation 3, to explain the effect of the Confining pressure and stress ratio on Resilient Modulus (Huurman, 1997).

$$M_r = k_1 \left(\frac{\sigma_3}{\sigma_0}\right)^{k_2} \left(1 \quad k_3 \left(\frac{\sigma_1}{\sigma_{1,f}}\right)^{k_4}\right) \qquad \text{(Eq. 3)}$$

Where, σ_3 and σ_1 is minor principal stress and major principal stress, kPa, respectively. $\sigma_{1.f}$ is major principal stress at failure, kPa. k_1 - k_4 are model constants.

2. EXPERIMENTATION

2.1 Material

The material tested in this study is crushed Hornfels, which is obtained from Contermanscloof quarry of Lafarge in Cape Town. Hornfels is a fine-textured metamorphic rock formed by contact metamorphism. Due to good mechanical properties it is usually used for base course in road pavement construction in South Africa. According to the South African specification the material used in this study is classified as G1 material, which requires that all of the surfaces are fractured, and the fine fraction is crushed from sound rock (Civil Engineering Advisor Council, 1998). According to the specification the aggregate shall not contain any deleterious material such as weathered rock, clay, shale or mica.

The crushed Hornfels is sieved into different fractions (0-0.6 mm, 0.6-2.36 mm, 2.36-9.5 mm, 9.5-13.2 mm, 13.2-19.0 mm, 19.0-26.5 mm), and then blended into mixture in line with the grading specification of nominal maximum 26.5 mm of G1 material. Figure 1 shows the grading curve of G1 material fitted with average limit. The passing percentage of 0.075 mm is 8.5 per cent.

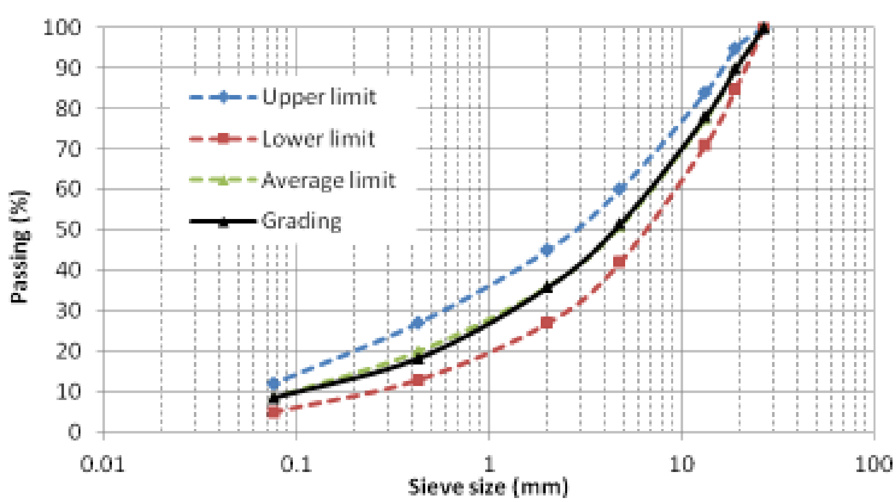

Figure 1 Grading curve of G1 material

The determination of apparent relative density was done complying with the South African specification TMH1 B14 and B15 (Technical Methods for Highways, 1986)

The apparent relative density (ARD) of 2750 kg/m^3 was obtained for G1 Hornfels mixture blended as average grading limit.

The modified AASHTO test was carried out to investigate the compaction property of blended G1 material according to TMH1 A7 (Technical Methods for Highways, 1986). The compaction curve shown in Figure 2 provided the relationship between dry density and moisture content. As can be seen from Figure 2, the maximum dry density (MDD) of 2365 kg/m^3 was achieved at optimum moisture content of 5.8 per cent by mass. The magnitude of maximum dry density is equivalent to 86 per cent of ARD of the aggregates.

The dimension of the specimen employed in this study is the same as the standard triaxial specimen 150 mm in diameter and 300 mm high. It is reported that material degradation can be reduced using vibratory compaction (Milberger and Dunlop, 1966). Therefore the vibratory compaction method is selected in the procedure of compaction. Correspondingly the vibratory hammer (Bosch GSH 11E) with surcharge 10 kg is employed for preparation of the specimens. Before that the compaction curve of vibratory hammer was calibrated on G1 material. This procedure is conducted by varying the moisture content from 3 per cent to 7 per cent increasing by 1 per cent increment. And the weigh applied onto the specimen is 10 kg. Each of 5 layers was compacted for 25 seconds to simulate the modified AASHTO compaction for each layer.

The compaction curve is also illustrated in Figure 2, which is above the compaction curve of modified AASHTO impact method. As shown in Figure 2, around 1 per cent reduction of moisture content existed between vibratory hammer compaction and modified AASHTO compaction. The maximum dry density is observed around 2389 kg/m^3 at optimum moisture content of 5.4 per cent, which is equivalent to 101 per cent maximum dry density of modified AASHTO density. 100 and 98 per cent of MDD can be drawn with 4.7 per cent and 4.3 per cent of moisture content according to the following compaction curves, respectively.

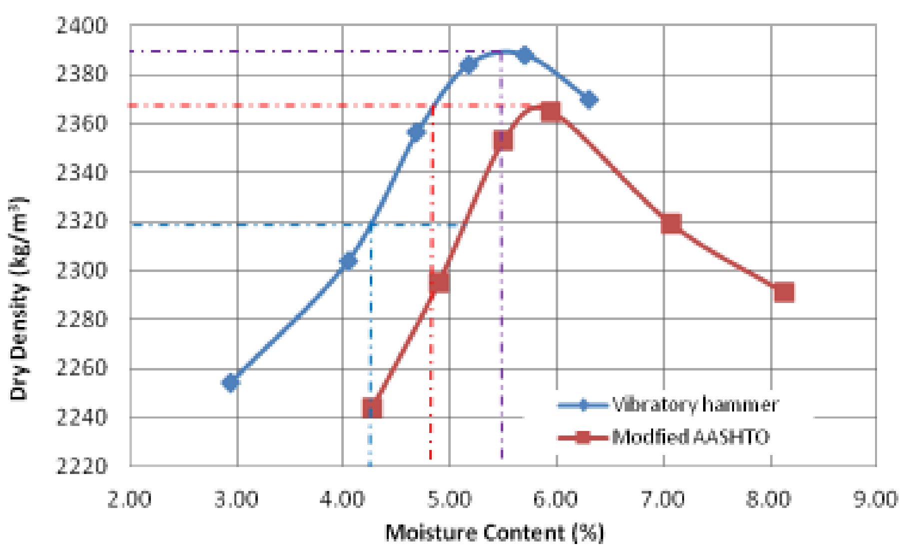

Figure 2 Determination of OMC and MDD for G1 material

2.2 Specimen preparation

It is well known that the shear properties and Resilient Modulus are largely determined by the density and the saturation of unbound materials. The density is mainly dependant on the degree of compaction (DOC). Therefore the experimental design should include the degree of compaction, expressing as a ratio of relative density to MDD or ARD of the blended material, and the degree of saturation, the volumetric percentage of the water to the total voids in the specimen. Three different levels of relative density combined with same degree of saturation 80 per cent were included in the experimental design, shown as in Table 1.

Table 1 Experiment design for the monotonic and cyclic triaxial tests

Dry Density (kg/m3)	Percentage of ARD	Percentage of MDD	Moisture Content (percentage)	Saturation (percentage)
2388	86.8	101.0	4.4	79.8
2365	86.0	100.0	4.7	79.4
2318	84.3	98.0	5.4	79.7

Prior to compaction sufficient granular material with an additional 10 per cent allowance for wastage was weighed out totally from each fraction according to the mass percentage listed in Table 1. The water to be added also was weighed by a volumetric cylinder according to the mass percentage in Table 2. The water was poured slowly into the material while the mixer is running. The material is mixed until the water is uniformly distributed throughout the material. The material of each layer was weighted out and sealed into plastic bags, and then appropriate amount of material used for determination of moisture content is weighted out as well. Each layer of specimen was compacted using the Bosch hammer for 25 seconds.

To approach the target moisture content, on one side, the wet specimens with excessive moisture was left and dried out in the room at ambient temperature until the actual mass reached the target mass and then underwent testing.

If, on the other hand, the mass of wet compacted specimens was less than the target mass, the specimens should be sealed in rubber membrane, which can provide sufficient confinement to allow this. The water required was then poured on top of the specimen at 50 ml increments. The specimens should be left for an hour before the next increment is added. Once the total mass of specimens reached the target wet mass, the specimen is sealed in a plastic bag and left for 24 hours to equilibrate before testing (Theyse, 2007).

2.3 Test details

2.3.1 Monotonic triaxial test

Monotonic failure triaxial tests were performed on the G1 base materials at 98 per cent, 100 and 101 per cent of MDD, and correspondingly the confining pressures are 20 kPa, 50 kPa and 80 kPa for each level of degree of compaction. The results of the monotonic triaxial tests were described by the well-known Mohr-Coulomb failure criterion and plotted on shear stress - normal stress space. The failure parameters of unbound granular material are characterized in terms of the cohesion (C) and the internal friction angle (φ), which can be obtained by regression analysis with following Equation 4:

$$\sigma_{1,f} = \frac{1+\sin\varphi}{1-\sin\varphi}\sigma_3 + \frac{2C\cos\varphi}{1-\sin\varphi} \qquad \text{(Eq. 4)}$$

The failure stress at each particular confining pressure is worked out from Equation 4. Thus the maximum principal stress applied during the cyclic triaxial test can be calculated in accordance with maximum stress ratio.

2.3.2 Resilient Modulus

Resilient Modulus testing is usually carried out using a triaxial cell set-up. The MTS (Material Test System) loading frame with a hydraulic actuator was employed during the test. The load cell is capable of applying a cyclic loading up to 50 KN. The confining pressure was supplied by pneumatic pressure, which was controlled by a valve with a pressure indicator. The vertical strain was captured by interior linear variable displacement transducers (LVDTs) and three on-specimen LVDTs mounted on the middle third of specimen.

Table 2 Test sequence for the Resilient Modulus testing of G1 material

Loading sequence	Confining pressure (kPa)	Major principal stress ratio	Repetitions
Conditioning	80	0.4	500
1	20	0.1	100
2	20	0.2	100
3	20	0.3	100
4	20	0.4	100
5	35	0.1	100
6	35	0.2	100
7	35	0.3	100
8	35	0.5	100
9	35	0.6	100
10	50	0.1	100
11	50	0.2	100
12	50	0.3	100
13	50	0.5	100
14	50	0.6	100
15	65	0.1	100
16	65	0.2	100
17	65	0.3	100
18	65	0.5	100
19	65	0.6	100
20	80	0.1	100
21	80	0.2	100
22	80	0.3	100
23	80	0.5	100
24	80	0.6	100

Note: the major principal stress ratio related to the ratio of the cyclic stress to failure strength ($\sigma_{1,f}$) at each confining pressure.

A typical haver sine pulse loading was applied on the top of specimen in vertical direction, which consists of a 0.1 second loading duration and a 0.9 second rest interval. This load cycle was established to simulate the application of traffic loads on the road pavement (Barksdale, 1971).

The cyclic stress levels imposed during the test were determined from the shear strength at given confinement. Tables 2 show the loading schedules for the Resilient Modulus testing of G1 material.

3. RESULTS AND DISCUSSION

3.1 Failure strength

The monotonic triaxial tests were conducted at the confining pressure of 20 kPa, 50 kPa and 80 kPa for each DOC. The Mohr-Coulomb circles of G1 material at 100 per cent DOC and 80 per cent of saturation were illustrated as Figure 3.

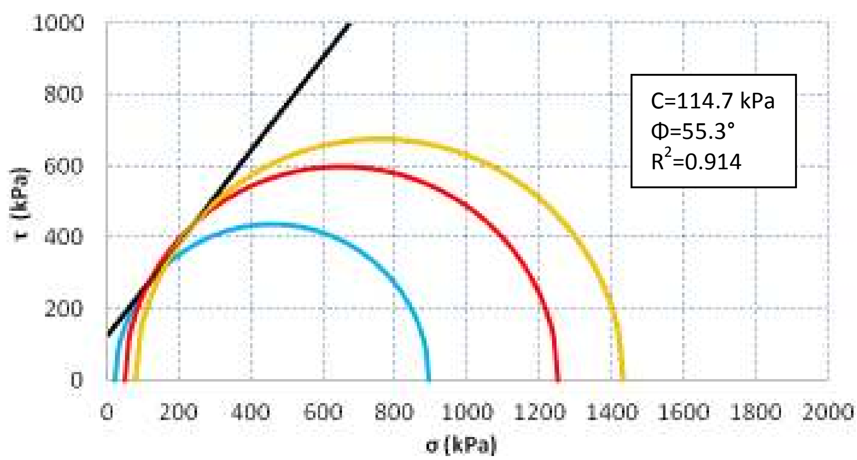

Figure 3 Mohr-Coulomb circles of G1 material at 100 per cent of DOC and 80 per cent of saturation

For G1 granular material at 80 per cent of saturation the Friction Angle increased from 53.1° to 56.8° as shown in Table 3.

Table 3 cohesion and internal friction angle of G1 material at different DOC

	98 per cent	100 per cent	101 per cent
C (kPa)	107.4	114.7	128.5
φ (°)	53.1	55.3	56.8
R^2	0.893	0.914	0.907

Also we can see in Table 3, the Cohesion increased from 107.4 kPa to 128.5 kPa with increasing degree of compaction. The correlation coefficient is approximately 0.9.

3.2 Evaluation of Resilient Modulus models

Resilient response of unbound granular materials is usually characterized by Resilient Modulus and Poisson's Ratio. For repeated load triaxial tests with constant confining pressure (CCP), the Resilient Modulus is defined as in Equation 5:

$$M_r = \frac{\Delta(\sigma_1 - \sigma_3)}{\varepsilon_r} \qquad \text{(Eq. 5)}$$

Where σ_1 and σ_3 are major and minor principal stress (kPa) respectively, ε_r is the major principal or axial resilient strain (per cent). $\Delta(\sigma_1 - \sigma_3)$ is the difference of deviator stress (kPa). The Resilient Modulus can be determined from the data of last 100 cycles of each loading stress ratio.

The model fit was carried out using nonlinear regression approach to achieve model parameters. Table 4 shows the regression results of models for different degree of compaction.

Table 4 Regression results of models at different DOC

	98 per cent of MDD			100 per cent of MDD			101 per cent of MDD		
	M_r-θ	Universal	TUD	M_r-θ	Universal	TUD	M_r-θ	Universal	TUD
k_1	6.513	2.845	5.543	7.704	3.718	10.614	8.757	4.547	28.27
k_2	0.674	1.586	0.957	0.679	2.998	1.126	0.684	1.624	0.867
k_3	-	-0.835	-6.086	-	-2.086	-4.315	-	-1.656	-2.886
k_4	-	-	0.267	-	-	0.474	-	-	0.575
R^2	0.878	0.935	0.960	0.848	0.903	0.956	0.903	0.945	0.953

As can be seen in Table 4, the TUD model fit the test data better than M_r-θ model and Universal model at all degree of compaction levels. The regression coefficient exceeded 0.950. The Universal model was reported as a model better than M_r-θ model physically in many studies. From the results listed in Table 4 it is observed that the universal model has a good agreement with the measured data. This model takes into account the influence of the deviator stress, which contributes to the shear failure of granular material.

From the model parameters it is obvious that the Resilient Modulus increased with the increasing degree of compaction. In other words, the compaction degree has a great influence on Resilient Modulus of granular material. Unfortunately the effluence of compaction degree, in other words relative density, is not incorporated into those models.

In this research only 80 per cent saturation was investigated in the tests, but note that the saturation degree also plays an important role in determination of Resilient Modulus. Theyse reported that the 80 per cent saturation in crushed Hornfels can increase confining pressure by 25 kPa (Theyse, 2007). A further study involved with the saturation degree or suction stress is required to model the Resilient Modulus more accurately for high quality crushed stone.

Figures 4-6 depicted the Resilient Modulus of various confining pressure at 100 per cent DOC and the prediction of different models in M_r-θ coordinate system.

Form Figure 4 and 5 it is observed that the M_r-θ model can't describe the increase of Resilient Modulus with increasing confinement. The prediction of Universal model indicated that the Resilient Modulus converged together at high stress levels, in the other words this model converged into M_r-θ model. But at low stress level it fitted the data very well than other two models.

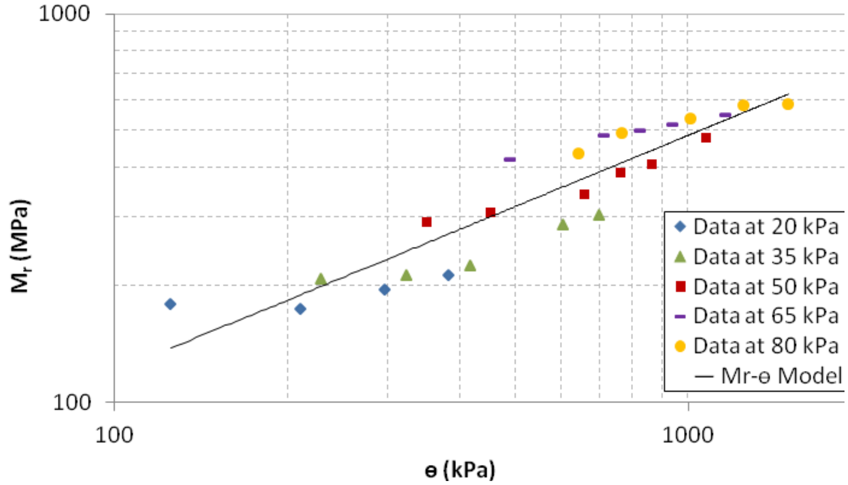

Figure 4 Resilient Modulus vs. bulk stress for test data and Mr-θ model

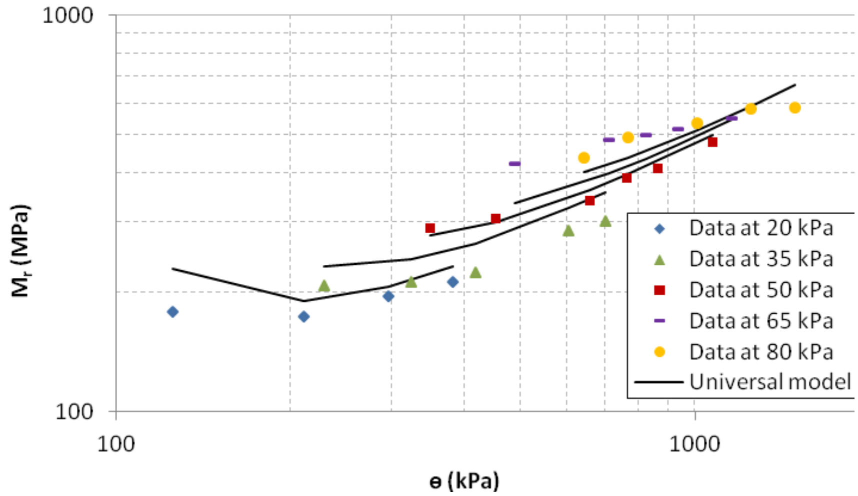

Figure 5 Resilient Modulus vs. bulk stress for test data and Universal model

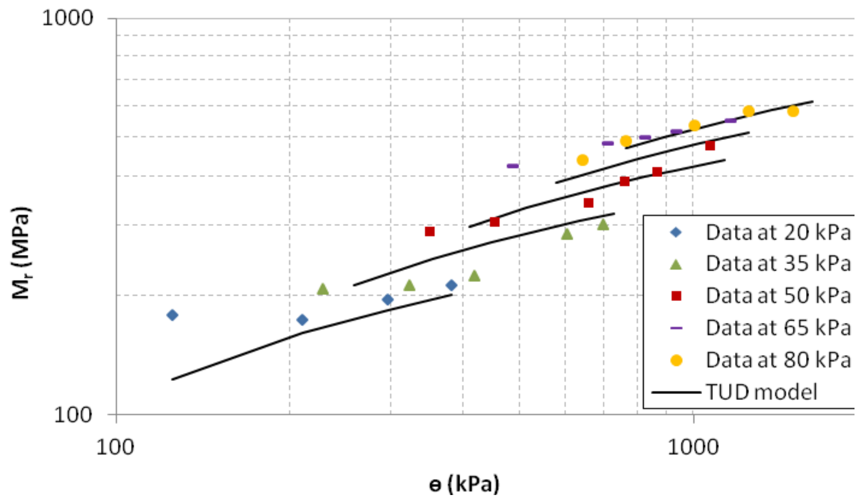

Figure 6 Resilient Modulus vs. bulk stress for test data and TUD model

As represented in Figure 6, the TU-Delft model obviously exhibits the strong dependence on Confining pressure. Because the same stress ratio was introduced in the test design, the second term of this model keeps the same at different confinement levels. But this model predicted Resilient Modulus better than other two models at high stress levels. The TU-Delft model also indicated that the incremental rate of Resilient Modulus reduced as the major principal stress approaching failure stress.

3.3 Matrix pressure dependent Resilient Modulus model

As discussed above, those classical models mainly takes the external stress into account. While actually internal stress (suction pressure) exists in unsaturated granular materials due to unsaturation state. Some researchers have reported that the suction stress in unsaturated granular material plays a very important role of the performance and proposed some models based on the effective stress concept (Cary and Zapata, 2010; Theyse, 2007; Liang et al, 2008).

It is widely known that the unsaturated granular material is consisted of aggregates and voids partially filled with water and air. So the amount of voids (relative density) and saturation of the voids have a great influence on the properties of granular material, basically due to the suction pressure, lubrication of water and compressibility of air. Thus a new model incorporating relative density and saturation should be proposed, and meanwhile based on effective stress conception.

Because the Universal model takes the shear stress into account, and which is based on a great amount of researches and has been prevailed, so the new model should concern the shear effect as well. The proposed variation to the universal model is expressed as follows:

$$M_r = \mathbf{k_1}\left[\left(\frac{\theta + \frac{\rho}{e^{\omega s}/d}}{p_a}\right)\right]^{k_2}\left(\frac{\tau_{oct}}{p_a} + 1\right)^{k_3} \qquad \text{(Eq. 5)}$$

Where θ is the bulk stress, kPa, s is the degree of saturation, per cent, d is the degree of compaction, per cent, τ_{oct} is the octahedral shear stress, kPa, p_a is the atmospheric pressure, kPa, ρ, ω are suction model parameters and k_1, k_2, k_3 are regression parameters.

Further studies are required to verify this model, and axial translation technique can be used to investigate the suction pressure of the granular material.

4. CONCLUSIONS

The well graded G1 material was prepared and compacted at three different densities at the same saturation in the laboratory. The monotonic and cyclic triaxial tests were carried out to obtain the failure and resilient properties. Three different models were selected and evaluated. The following conclusions can be drawn:

G1 crushed stone exhibits good shear resistance due to high cohesion force and internal fraction angle.

The M_r-θ, Universal and TU-Delft model fitted the measured data very well to some extent. The TU-Delft and Universal are more capable of prediction of the Resilient Modulus of unbound material for road pavement.

The prediction of Universal model indicated that the Resilient Modulus converged together at high stress levels, while the TU-Delft model predicted Resilient Modulus better than other two models at high stress levels.

A new model incorporating density and saturation based on effective stress based on effective stress conception was proposed for modeling Resilient Modulus of unsaturated unbound material.

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KEYWORDS

Granular material; Resilient Modulus; crushed stone; base course