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USE OF CBR MOULD FOR EVALUATION OF CONSTRAINED MODULUS-BULK STRESS RELATIONS OF PAVEMENT STRUCTURE MATERIALS

Sawanya Dararat[1] and *Warat Kongkitkul[2]

[1,2]Department of Civil Engineering, Faculty of Engineering,
King Mongkut's University of Technology Thonburi, Thailand

*Corresponding Author, Received: 30 June 2016, Revised: 15 July 2016, Accepted: 26 Nov. 2016

ABSTRACT: One of important parameters used in the mechanistic pavement engineering design is resilient modulus (M_R) of pavement structure materials. In general, M_R is evaluated in a complicated and thus expensive triaxial compression test in that a number of repeated loads are applied at various stress states. This research presents an alternative method to determine the constrained modulus (M) of a dried sand, a lateritic soil and a crushed rock, under one-dimensional compression. At various vertical stress levels, M values were determined by applying small strain-amplitude cyclic loadings to the compacted soil specimens prepared in a CBR mould. In the present study, the CBR mould was made special in that it can measure the lateral stress confining to the specimen during a test. Hence the bulk stress (θ) can then be determined, and M-θ relations for the tested materials were presented. In addition, an analytical method for eliminating the effects of bedding error was attempted so as to obtain the true M value. It is found that M is not constant but increases with θ, similar to M_R-θ relations found with the resilient modulus test. In addition, the bedding error is important and can result in a significant underestimation of the true M value.

Keywords: Pavement Structure Materials, Constrained Modulus, Resilient Modulus, Coefficient of Lateral Earth Pressure, Bedding Error

1. INTRODUCTION

Resilient modulus (M_R) of pavement structure materials is an important parameter used in the mechanistic pavement engineering design. Resilient modulus is a property of the pavement system corresponding to repeated traffic loadings. The resilient modulus laboratory testing of soil and aggregate materials has been recommended by AASHTO T307 [1]. Triaxial apparatus is widely used for evaluation of resilient modulus of pavement structure materials [2]-[5]. To utilise the M_R from triaxial test results, k-θ model is the most commonly used for granular materials in the pavement engineering design (Eq. (1)).

$$M_R = k_1\theta^{k_2} \quad (1)$$

where k_1 and k_2 are regression constants

However, preparation of test specimens and shear loading history employed in the triaxial tests for evaluation of M_R are complicated, and therefore difficult, expensive and time consuming. On the other hand, the resilient modulus can be estimated from correlations with California Bearing Ratio (CBR) [6], [7]. It is of great interest in the present study to determine the resilient modulus or a similar parameter that represents the elastic stiffness directly from the specimen prepared with the standard CBR mould.

To this end, many researchers have developed alternative methods to evaluate the material's stiffness for the pavement engineering design purpose, for example, the K-Mould [8], Springbox [9], and PUMA [10]. On the other hand, one-dimensional cyclic loading test on a specimen prepared in a CBR mould is easy to conduct in laboratory. Then constrained modulus (M) can be determined. However, this test method could not measure the lateral stress. It is therefore necessary to modify the standard CBR mould so that the measurement of lateral stress is possible. In this study, a CBR mould was attached with strain gauges to measure the hoop strain and converts to the lateral stress. Then the coefficient of lateral earth pressure at rest (K_0) was determined. Hence, the bulk stress (θ), which is summation of all the normal stresses, can then be determined. Then, at the same θ, M and M_R could be compared, and if there are correlations, M_R could be estimated from M, which can be reliably determined in a much easier method. In addition, the usual measurement of specimen's compression always includes the so-called bedding error which significantly affects the determined material's stiffness. In this study, it was attempted to prepare test specimens with different heights and used the correction procedures proposed by Koseki et al. [11] to determine the true M value that is free from any bedding error.

Summarising the above, in this study, it was attempted to evaluate the constrained modulus of pavement structure materials, and eliminate the bedding error from one-dimensional cyclic loading tests. A special CBR mould was used to evaluate lateral stress confined to the test specimen.

2. MATERIALS AND APPARATUSES

2.1 Test Materials

Three materials used in the test program of the present study were KMUTT sand, lateritic soil, and crushed rock. Fig.1 shows their particle size distributions. KMUTT sand was air-dried and used to verify the test program and the special CBR mould (explained later). The lateritic soil and crushed rock materials were prepared at 100% of maximum dry density (MDD) and optimum moisture content (OMC). The compaction curves are shown in Fig.2. Table 1 lists the OMC and MDD of lateritic soil and crushed rock.

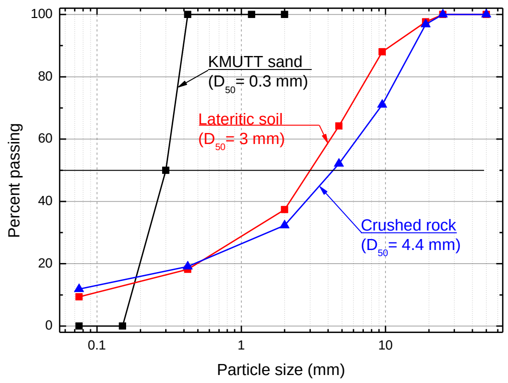


Fig.1 Particle size distributions of tested materials.

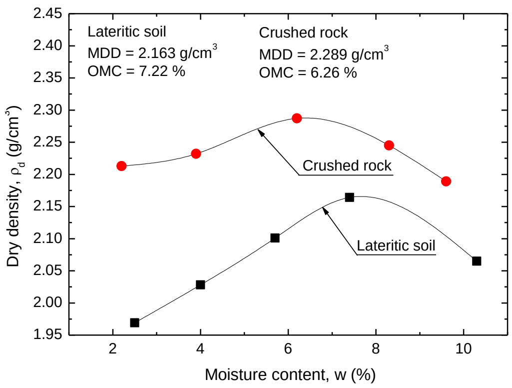


Fig.2 Compaction curves of lateritic soil and crushed rock.

2.2 Apparatuses

A cylindrical metal mould with an inner diameter of 152.4 mm and a height of 177.8 mm (without the collar) was used. This mould is in accordance to ASTM D 1883-99. By using this mould, the lateral deformation of specimen is confined, while it is allowed to deformed only in the vertical direction. A special CBR mould, which was attached with strain gauges, was used (Fig.3). To measure the hoop strain, two strain gauges attached on the opposite sides of the mould, and then connected with the other two fix resistors to form a full Wheatstone bridge circuit (opposite side 2-active-gauge) (Fig.3).

Table 1 Compaction test results of lateritic soil and crushed rock

Materials	OMC (%)	MDD (g/cm^3)
Lateritic soil	7.22	2.163
Crushed rock	6.26	2.289

3. TEST METHODS

3.1 Specimen Preparation

A KMUTT sand specimen was prepared by pluviation through the air. The density thus obtained is around 1.52 g/cm^3. The lateritic soil and crushed rock specimens were prepared by compacting the respective materials that were laid layer-to-layer into the mould. Three types of specimen with the different specimen's heights of 177.8 mm, 142.2 mm, and 106.7 mm were prepared for each type of test materials.

3.2 Test Program

Two loading patterns were employed, as shown in Fig.4. They are: i) continuous monotonic loading with a constant strain rate (ML); and ii) sustained loading (SL) and then followed by cyclic loading (CL). In the latter loading pattern, monotonic loading is applied firstly until the target vertical stress has reached, and then sustained loading is performed for 30 minutes. Next, cyclic loading with a double stress-amplitude of 30 kPa are applied for 10 cycles, subsequently monotonic loading is applied again to the next target vertical stress (Fig.4). Test program in the present study is shown in Table 2.

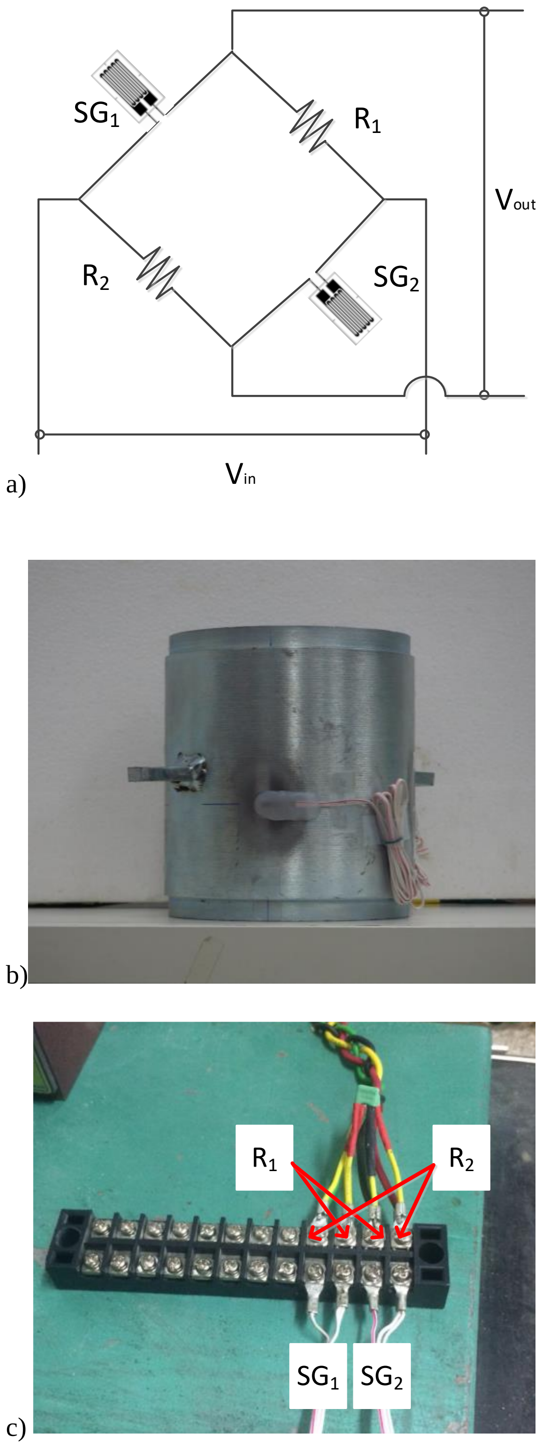


Fig.3 Configurations of the special CBR mould: (a) a full Wheatstone bridge with two active gauges and two fix resistors; (b) strain gauges attached on the mould's side; and (c) connections of strain gauges and fix resistors using a terminal.

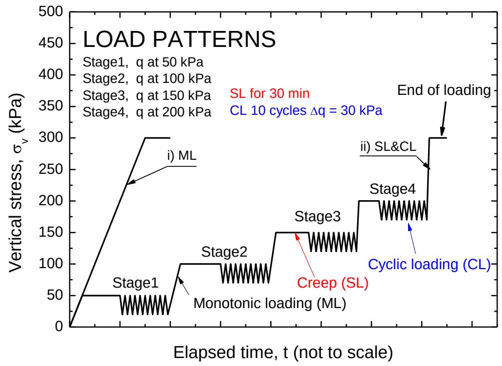


Fig.4 Loading histories.

Table 2 Test program used in the present study

Materials	Initial height	Load Patterns
KMUTT Sand	H	ML
	H, 0.8H, 0.6H	ML, SL ,CL
Lateritic soil	H	ML
	H, 0.8H, 0.6H	ML, SL ,CL
Crushed rock	H	ML
	H, 0.8H, 0.6H	ML, SL ,CL

Note: H = Basic initial specimen's height, equal to 177.8 mm

4. TEST RESULTS AND DISCUSSIONS

4.1 Monotonic Loading Test Results

Figures 5(a), 5(b), and 5(c) show the variation of vertical stress (σ_V) and horizontal stress (σ_h) with vertical strain (ε_V) from ML tests on KMUTT sand, lateritic soil, and crushed rock, respectively. In these tests, stress-strain curves exhibit continuous strain-hardening behaviour. Here, it was assumed in the present study that the tangential strain (ε_θ) mobilised on surface of the CBR mould during a test is uniform along the height and the periphery. The ε_θ value measured by the strain gauges is therefore the representative of the entire CBR mould. Then, the horizontal stress can be calculated from Eq. (2), based on the theory of stress in a cylindrical elastic material.

$$\sigma_h = \frac{\varepsilon_\theta E t}{r} \tag{2}$$

where E, t, and r are Young's modulus, thickness, and radius of the CBR mould, respectively. It may be necessary to calibrate the horizontal stress determined by the technique described above with other relevant techniques that can directly measure the horizontal stress so as to assure the measurement accuracy and precision. However, it is not presently known to the authors how this calibration shall suitably be performed.

Coefficient of lateral earth pressure at rest ($K_0 = \sigma_h/\sigma_v$) of tested materials are shown in Figs. 6(a), 6(b), and 6(c), for KMUTT sand, lateritic soil, and crushed rock, respectively. For a numerical simulation in the pavement engineering analysis, K_0 of the base and subbase materials are typically selected at 0.30-0.42 [12], [13]. However, K_0 of lateritic soil and crushed rock determined from the present study are around 0.4-0.5. Further investigations on accuracy of the use of lateral stress

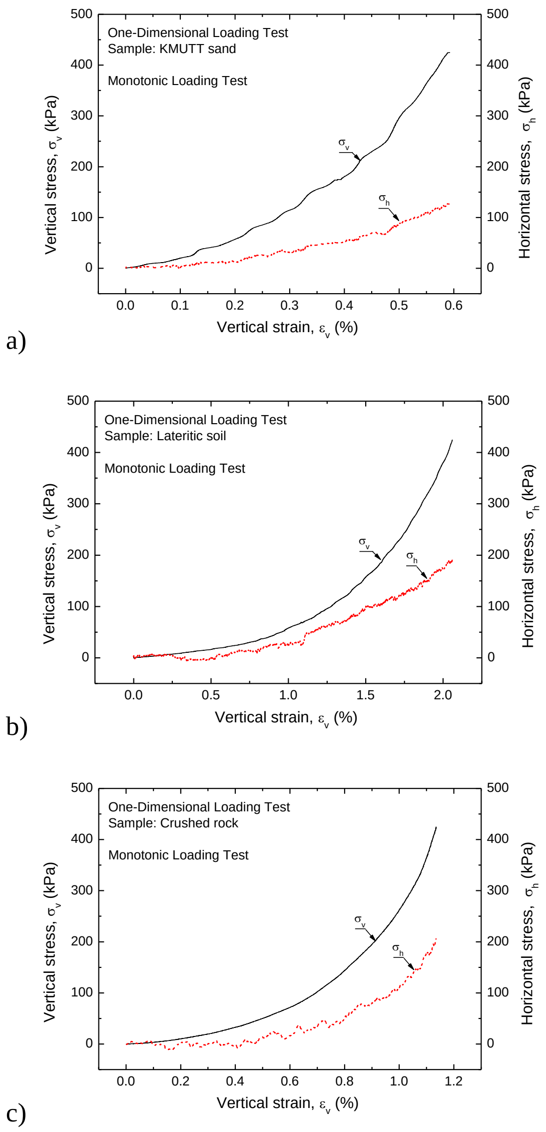


Fig.5 Vertical stress and horizontal stress – axial strain relations from one-dimensional monotonic loading tests on: (a) KMUTT sand; (b) lateritic soil; and (c) crushed rock.

measurement technique developed in this study is necessary to examine such slight discrepancies mentioned above.

4.2 Constrained Modulus from CL Tests

Figures 7(a), 7(b), and 7(c) show the unloading braches Nos. 6-10 at the stress level of 100 kPa for KMUTT sand, lateritic soil, and crushed rock, respectively. The stress-strain behaviour along these branches is highly linear only for a smaller range of stress increment of the stress-strain loop.

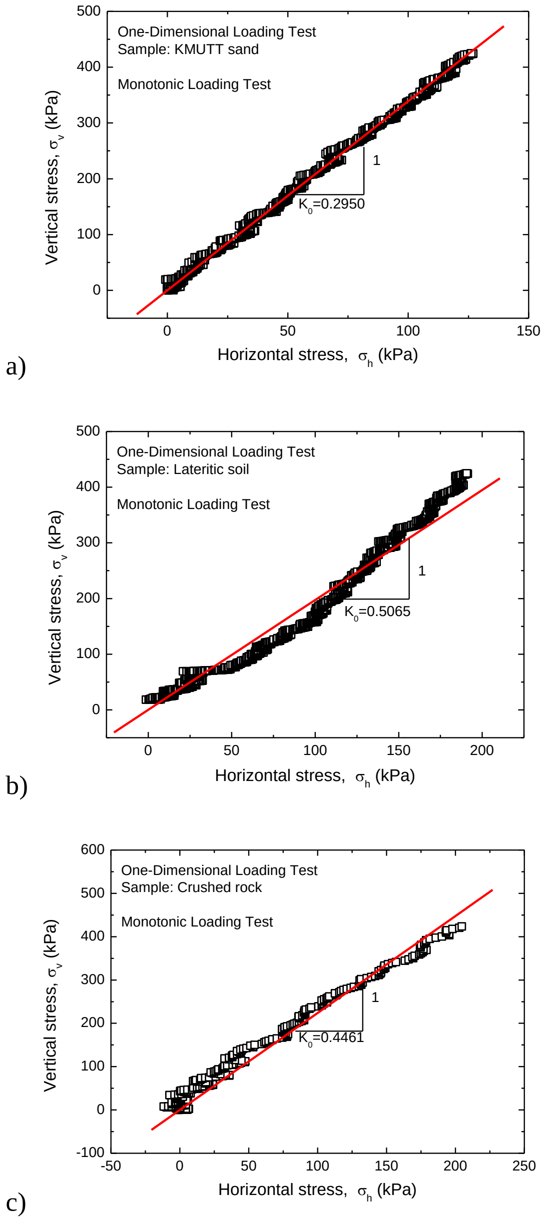
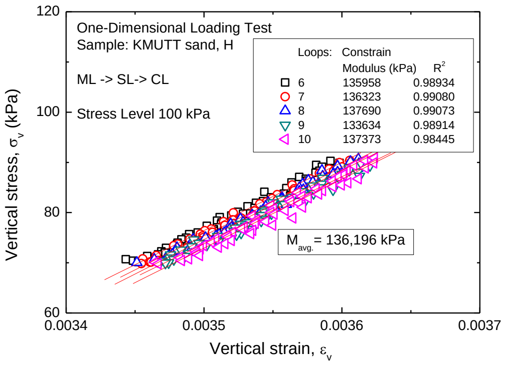
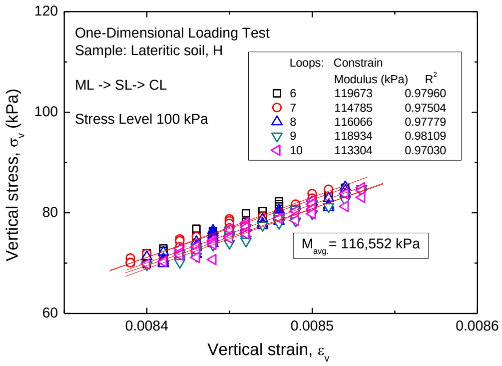


Fig.6 Relationships between vertical stress and horizontal stress of: (a) KMUTT sand; (b) lateritic soil; and (c) crushed rock.

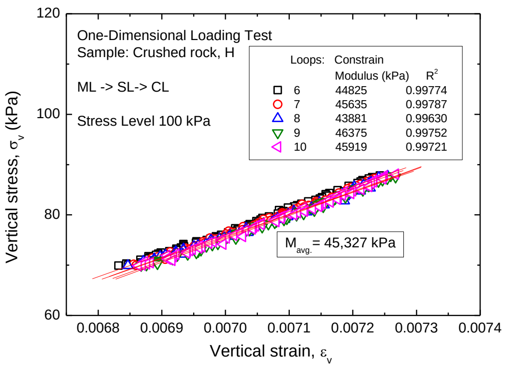
Lines were best-fitted to the respective unloading branches presented in Fig. 7 to obtain the constrained modulus (M). Then, the relationships between M and bulk stress ($\theta = \sigma_v + 2\sigma_h$) where $\sigma_h = K_0\sigma_v$ for different types of specimen specified by different specimen's heights were plotted for KMUTT sand, lateritic soil, and crushed rock as shown in Figs.8(a), 8(b), and 8(c), respectively. It can be clearly seen that the M value increases significantly with an increase in the stress level [2], [4], [6], [14]. Due to an error of axial deformation measurement found with the tests on KMUTT sand and lateritic soil using the specimens with the heights of 0.6H and 0.8H, the M value can be confidently determined only at the stress level of 50 kPa. The data points at the higher stress levels for these two materials were obtained by extrapolations using the relation obtained for the specimen with the height of H to pass through the only data point measured at the stress level of 50 kPa, as shown in Figs. 8(a) and 8(b).



a)

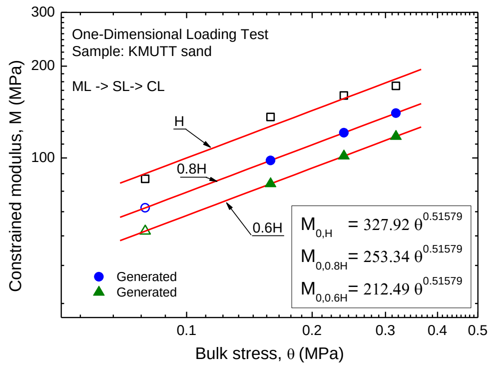


b)

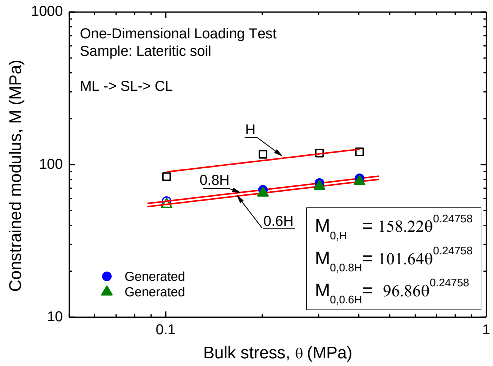


c)

Fig.7 Unloading braches of vertical stress-vertical strain relations used to determine the constrained modulus at the stress of level 100 kPa on: (a) KMUTT sand; (b) lateritic soil; and (c) crushed rock.



a)



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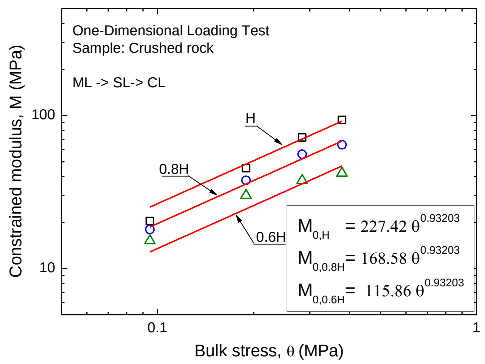


c)

Fig.8 Relationships between constrained modulus and bulk stress of: (a) KMUTT sand; (b) lateritic soil; and (c) crushed rock.

4.3 Evaluation of Effects of Bedding Error on Constrained Modulus

In order to evaluate effects of bedding error on the measured constrained modulus, the analytical procedures proposed by Koseki et al. [11] was used. According to Eq. (3), a constrained modulus of a bedding error layer (M_1) and the constrained modulus of the normal layer (M_2) can be evaluated from relationships between $1/M_0$ and $1/H$ [11].

$$\frac{1}{M_0} = \left(\frac{1}{M_1} - \frac{1}{M_2}\right)\frac{D_{50}}{H} + \frac{1}{M_2} \tag{3}$$

where M_0 is nominal value of the constrained modulus evaluated in a conventional manner for the whole specimen height, H is height of a specimen, and D_{50} is particle mean diameter. In the present study, M_0 is therefore the measured M value shown in Fig.8, which is dependent on the specimen's height (H) and the bulk stress (θ), and M_2 is the constrained modulus of test material that is free from any bedding error and independent of the specimen's height, while still dependent on the bulk stress (θ).

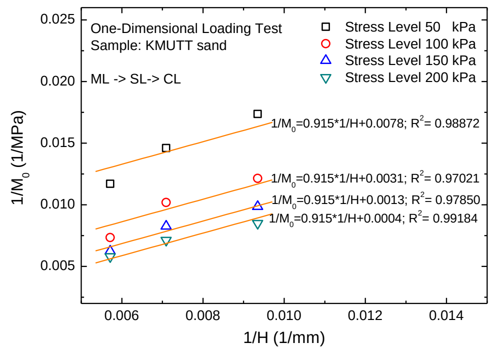
Figures 9(a), 9(b), and 9(c) show relationships between $1/M_0$ and 1/H for KMUTT sand, lateritic soil, and crushed rock, respectively. It can be seen that for the same stress level, the value of $1/M_0$ increased with an increase in the value of 1/H. Lines were best-fitted by assuming that the slopes for different stress levels are the same.

Table 3 Nominal constrained modulus and estimated values of bedding error layer and normal layer

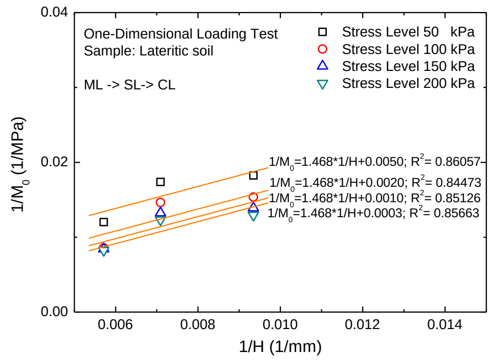
Tested material	Stress Level (kPa)	M_0 (MPa)	M_1 (MPa)	M_2 (MPa)
KMUTT sand	50	57, 68, 85	0.33	128
	100	82, 98, 136	0.33	322
	150	101, 120, 160	0.33	769
	200	117, 140, 172	0.33	2500
Lateritic soil	50	55, 57, 83	2.02	200
	100	65, 68, 116	2.04	500
	150	72, 75, 119	2.04	1000
	200	77, 81, 121	2.04	3333
Crushed rock	50	15, 18, 20	1.16	34
	100	30, 37, 45	1.20	3333
	150	37, 56, 72	1.21	-140
	200	42, 64, 93	1.22	-98

The values of constrained modulus are summarised in Table 3. The M_2 values are significantly larger than the respective M_0 values. On the other hand, the constrained modulus values of the bedding error layers (M_1) are substantially smaller than the respective M_2 values.

The M_2 values of crushed rock at the stress levels of 150 and 200 kPa exhibited negative values. This may be resulted from larger particles contained in the specimen in the mould [11]. However, all the M_2 values obtained from the present study should be compared and/or calibrated with the triaxial compression test results. However, this work is beyond the scope of the paper.



a)



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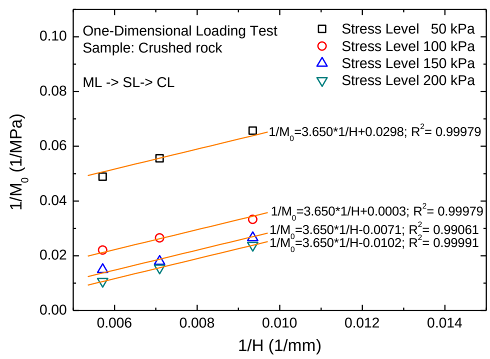

c)

Fig.9 Relationships between $1/M_0$ and 1/H of: (a) KMUTT sand; (b) lateritic soil; and (c) crushed rock.

5. CONCLUSIONS

The following conclusions can be derived from the test results presented in this study:

1. Coefficient of lateral earth pressure at rest can be determined from the newly developed special CBR mould attached with strain gauges for the measurement of tangential strain.
2. Constrained moduli of KMUTT sand, lateritic soil, and crushed rock are not constant but increase with an increase in the vertical stress level.
3. Constrained modulus that is free from bedding error can be determined by performing tests with different specimen's heights. By using an analytical method reported in the literature, it is found that the bedding error can result in a significant underestimation of constrained modulus.

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