# Default k-Values for Estimating Resilient Modulus of Coarse-Grained Nigerian Subgrade Soils

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**Abstract.** In this paper subgrade materials from different locations in Nigeria were characterized for use in the Mechanistic-Empirical Pavement Analysis and Design. The engineering properties of the coarse-grained Nigerian subgrade soils materials were obtained in the laboratory. Seven selected resilient modulus constitutive equation for estimating the resilient modulus of coarse-grained subgrade soils were used to estimate the default values using the repeated load triaxial test result conducted on coarse-grained Nigerian subgrade soils. These default resilient modulus parameters developed can be used to estimate the resilient modulus of the compacted subgrade soils with reasonable accuracy and utilized as level 3 resilient modulus input for Mechanistic-Empirical Pavement Analysis and Design.

**Keywords:** Coarse-grained soils · Resilient modulus · Mechanistic-Empirical · Flexible pavement · Subgrade soils

## 1 Introduction

A conventional flexible pavement consists of a prepared subgrade or foundation and layers of sub-base, base and surface courses (AASHTO 1993).

For the roadbed soils, the seasonal variation of resilient moduli is considered and used directly to determine the design or effective roadbed soil resilient modulus. However, seasonal variation of the resilient moduli for pavement materials is not used or considered in the design process, even though the resilient modulus of pavement materials can vary substantially throughout the year (Von Quintus and Killingsworth 1997).

The design and evaluation of pavement structures on base and subgrade soils requires a significant amount of supporting data such as traffic loading characteristics, base, subbase and subgrade material properties, environmental conditions and construction procedures. Characterization of pavement materials is a key requirement for the pavement design process. The characterization task involves obtaining material properties that identify the material response to external stimuli of traffic loading and environmental conditions. Characterization of subgrade materials using resilient modulus involves obtaining material properties (index properties, physical and compaction properties) that identify the material response to external stimuli of traffic loading and environmental


W. Frikha et al. (eds.), *Soil Testing, Soil Stability and Ground Improvement*,
Sustainable Civil Infrastructures, DOI 10.1007/978-3-319-61902-6_17

conditions. In its 2002 design guide, the AASHTO advocated the use of the resilient modulus parameter for describing granular material behaviour. Laboratory techniques provide a means for directly measuring the resilient modulus parameter, wherein the process usually involves elaborate and extensive testing at various stress levels and physical conditions to completely map the range of the resilient modulus parameter for any material under consideration. To be able to adopt the Mechanistic-Empirical pavement design method for use in Nigeria, calibration of the subgrade material models to reflect Nigerian conditions need to be carried out.

A more widely used recent test method on which pavement designs are based is the resilient modulus value. It is defined as the ratio between repeated deviator stress and resilient strain. The laboratory testing procedures for determining the resilient modulus values is time consuming and needs expensive equipment and highly trained personnel (Vogrig et al. 2003).

The resilient modulus is a fundamental engineering material property that describes the non-linear stress-strain behaviour of pavement materials under repeated loading. It is defined as the ratio of the maximum cyclic stress to the recoverable resilient (elastic) strain in a repeated dynamic loading (Mohammad et al. 2007).

It is a measure or estimate of the elastic modulus of the material at a given stress or temperature. Mathematically it is expressed as the ratio of applied deviator stress to recoverable strain (George 2004).

In Level 1 design/analysis, the MEPDG requires input of the regression constants of the stress-dependent constitutive equation for resilient modulus of a particular unbound material (subgrade soil or base aggregate). This ensures a more accurate assessment of the modulus during the analysis over the design period including seasonal variation and varying stress conditions. Constitutive equation coefficients (k-values) are usually obtained from the regression analysis of resilient modulus test data for an actual soil/aggregate sample (Hossain 2010).

Some agencies consider the cost, time, complication, and sampling resolution required for meaningful resilient modulus testing to be too cumbersome for its application in less critical projects. Regardless of project size, it is often difficult to predict and consequently reproduce the in-situ conditions, usually with respect to the state of stress, further complicating the use of resilient modulus testing. Because of this, correlations are desired for estimating resilient modulus, especially for use (or verification of default values) associated with MEPDG Level 2 design/analysis. A common method to predict a resilient modulus value is to use the stress-dependent constitutive equation with the k-values estimated from soil index properties through further regression equations. MEPDG Level 3 design/analysis also requires a specific resilient modulus value as input (Hossain 2010).

## 2 Resilient Modulus Constitutive Models

Mathematical models are generally used to express the resilient modulus of subgrade soils such as the bulk stress model and the deviatoric stress model. These models were utilized to correlate resilient modulus with stresses and fundamental soil properties.

A valid resilient modulus model should represent and address most factors that affect the resilient modulus of subgrade soils (Titi et al. 2006).

Several other models were reported in the literature, which use both stresses (either confining and deviatoric stresses or bulk or octahedral stresses) that are functions of confining and deviatoric stresses. The most general form of a three-parameter model is as shown in Eq. 1 (Ooi et al. 2006; NCHRP 2008):

$$M_R = k_1 P_a [f(c)]^{k_2} [g(s)]^{k_3} \tag{1}$$

where $f(c)$ is a function of confinement; $g(s)$ is a function of shear and $k_1$, $k_2$, and $k_3$ are constants.

The effects of confinement in these models can be expressed in terms of the minor principal stress ($\sigma_3$), bulk stress ($\theta$), or octahedral stress ($\sigma_{oct} = \theta/3$), while the parameter options for modelling the effects of shear include the deviatoric stress or octahedral shear stress ($\tau_{oct}$). The three-parameter models represented by the Eq. 1 are more versatile and apply to all soils (NCHRP 2008).

Uzan (1985) studied and discussed different existing models for estimating resilient modulus. The Uzan equation was developed as a combination of the bulk and deviator stress models in an effort to improve the predicted response of $M_r$ test results by including both axial and shear effects. The model defined the resilient modulus as shown in Eq. 2 (Uzan 1985; NCHRP 2008):

$$M_R = k_1 P_a \left(\frac{\theta}{P_a}\right)^{k_2} \left(\frac{\sigma_d}{P_a}\right)^{k_3} \tag{2}$$

where $k_1$, $k_2$, and $k_3$ are material constants; $\theta$ = bulk stress; $\sigma_d$ = deviatoric stress; $P_a$ is the atmospheric pressure

An equation similar to Uzan's model using the octahedral shear stress instead of the deviator stress was developed by Witczak and Uzan as shown in Eq. 3 (Witczak and Uzan 1988; NCHRP 2008):

$$M_R = k_1 P_a \left(\frac{\theta}{P_a}\right)^{k_2} \left(\frac{\tau_{oct}}{P_a}\right)^{k_3} \tag{3}$$

where $\theta$ = bulk stress ($\sigma_1 + \sigma_2 + \sigma_3$); $\sigma_1$ = major principal stress

$\sigma_2$ = intermediate principal stress = $\sigma_3$ for $M_R$ test on cylindrical specimen.

$\sigma_3$ = minor principal stress/confining pressure; $\tau_{oct}$ = Octahedral shear stress.

$$\tau_{oct} = \frac{1}{3}\left((\sigma_1 - \sigma_2)^2 (\sigma_2 - \sigma_3)^2 (\sigma_3 - \sigma_1)^2\right)^{1/2}$$

An equation similar to Uzan's model using the confining pressure instead of the bulk stress was recommended by Pezo as shown in Eq. 4 (Pezo 1993; NCHRP 2008):

$$M_R = k_1 P_a \left(\frac{\sigma_3}{P_a}\right)^{k_2} \left(\frac{\sigma_d}{P_a}\right)^{k_3} \tag{4}$$

An equation similar to Pezo's model using the confining pressure and deviator stress in a three-parameter formulation was recommended by Ni et al. as shown in Eq. 5 (Ni et al. 2002; NCHRP 2008):

$$M_R = k_1 P_a \left(1 + \frac{\sigma_3}{P_a}\right)^{k_2} \left(1 + \frac{\sigma_d}{P_a}\right)^{k_3} \tag{5}$$

Ooi et al. slightly modified the equation recommended by Ni et al. using the bulk stress, octahedral shear stress and deviator stress in a three-parameter formulation into two models as shown in Eqs. 6 and 7 (Ooi et al. 2004; NCHRP 2008):

$$M_R = k_1 P_a \left(1 + \frac{\theta}{P_a}\right)^{k_2} \left(1 + \frac{\sigma_d}{P_a}\right)^{k_3} \tag{6}$$

$$M_R = k_1 P_a \left(1 + \frac{\theta}{P_a}\right)^{k_2} \left(1 + \frac{\tau_{oct}}{P_a}\right)^{k_3} \tag{7}$$

An equation similar to Ooi et al.'s model using the octahedral shear stress and bulk stress was recommended by the NCHRP project 1-28 A as shown in Eq. 8 (NCHRP 2008):

$$M_R = k_1 P_a \left(\frac{\theta}{P_a}\right)^{k_2} \left(1 + \frac{\tau_{oct}}{P_a}\right)^{k_3} \tag{8}$$

## 3 Evaluation of the Resilient Modulus Model Parameters for Coarse-Grained Soils

The resilient modulus of coarse-grained soils obtained in the laboratory were statistically analysed. These values were used in evaluating the $M_r$ parameters of the coarse-grained soils using the seven resilient modulus equations presented in literature. Figures 1a, 1b, 1c, 2a, 2b, 2c, 3a, 3b, 3c, 4a, 4b, 4c, 5a, 5b, 5c, 6a, 6b, 6c, 7a, 7b and 7c presents the histogram of the resilient modulus parameters ($k_i$) values of coarse-grained soils obtained from the resilient modulus equations evaluated.

Figure 1a, 1b and 1c shows the histogram of resilient modulus parameters ($k_i$) values obtained from Uzan model.

Figures 2a, 2b and 2c present the histogram of the resilient modulus model

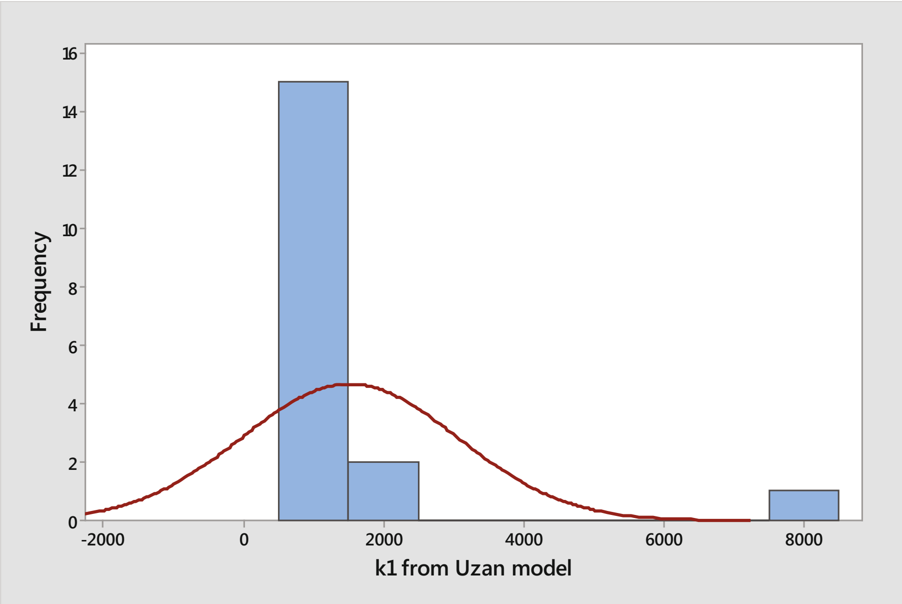


**Fig. 1a.** Histograms of Uzan resilient modulus model parameters $k_1$

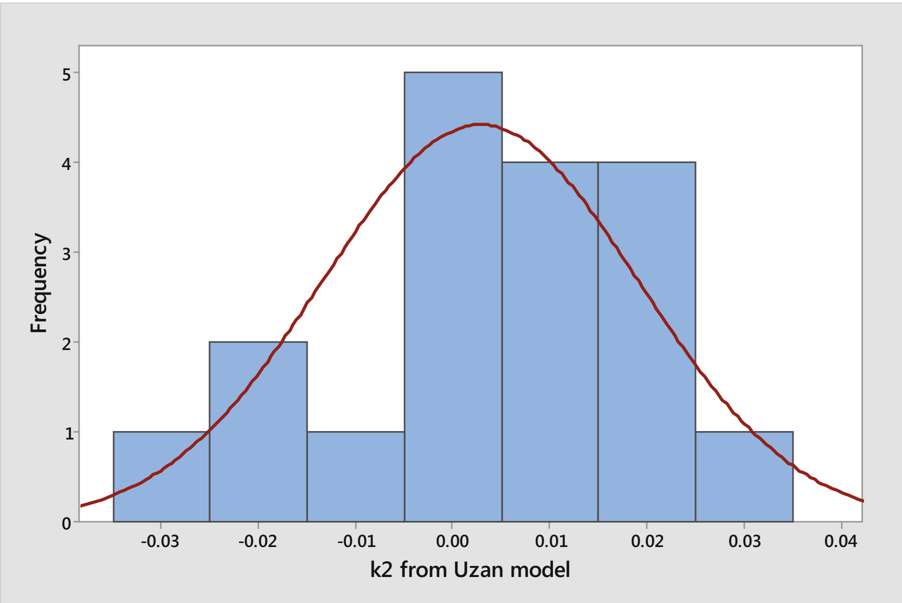


**Fig. 1b.** Histograms of Uzan resilient modulus model parameters $k_2$

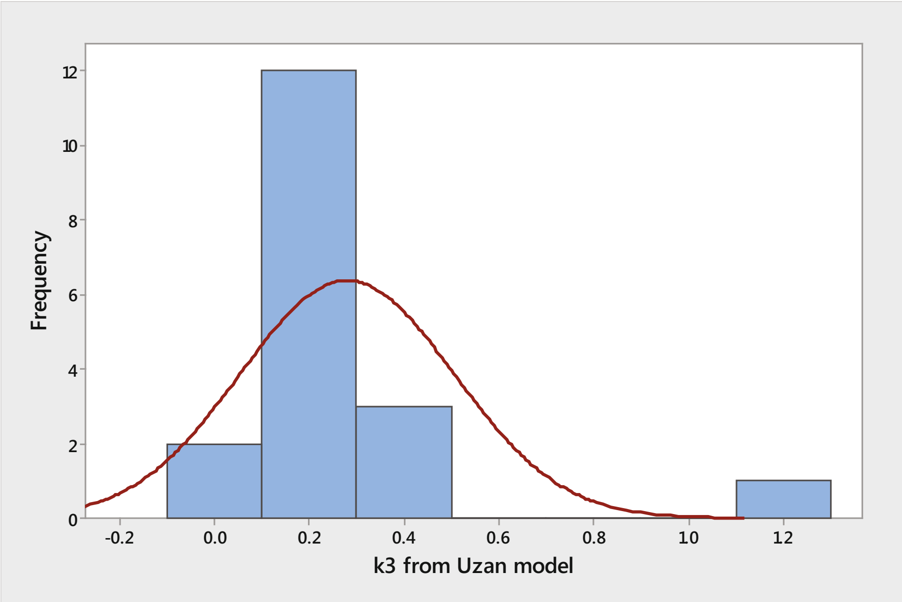


**Fig. 1c.** Histograms of Uzan's resilient modulus model parameters $k_3$

parameters $k_i$ obtained using the Witczak and Uzan resilient modulus model.

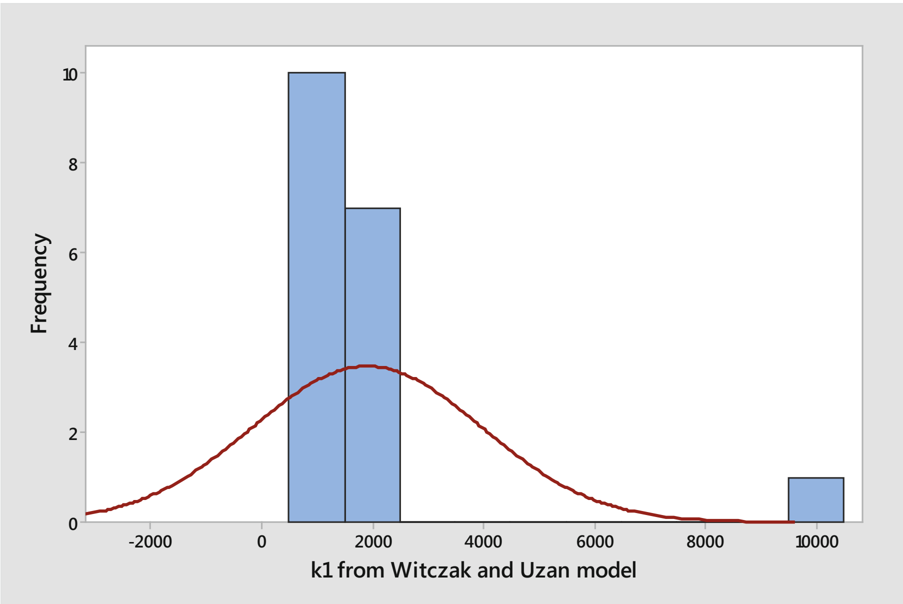


**Fig. 2a.** Histograms of Witczak and Uzan resilient modulus model parameters $k_1$

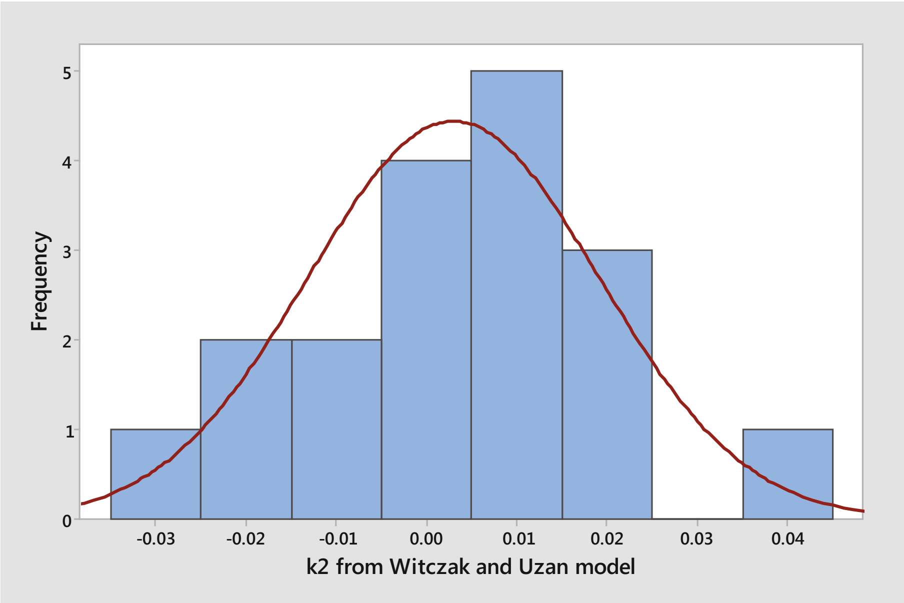


**Fig. 2b.** Histograms of Witczak and Uzan resilient modulus model parameters $k_2$

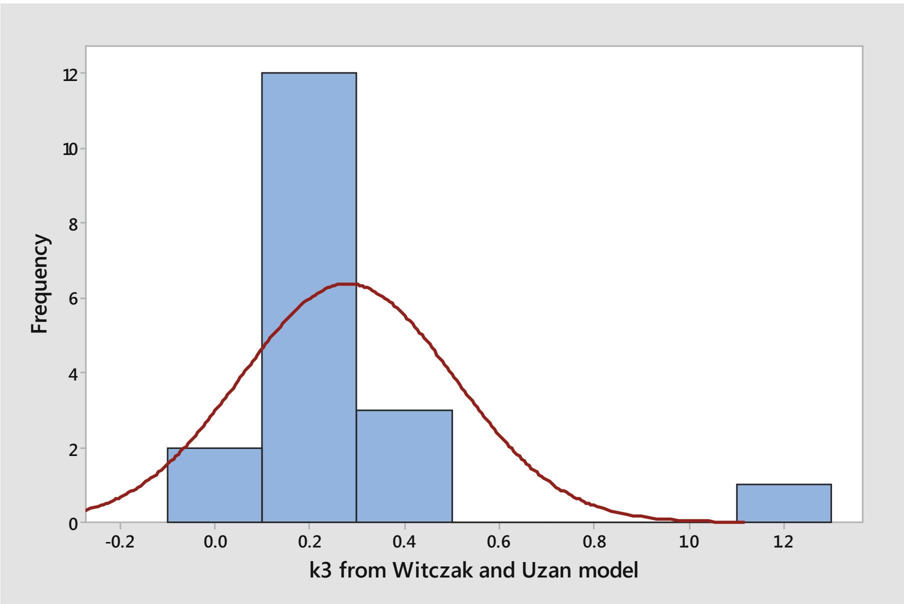


**Fig. 2c.** Histograms of Witczak and Uzan resilient modulus model parameters $k_3$

Figures 3a, 3b and 3c present the histogram of the resilient modulus model parameters $k_i$ obtained using the Pezo resilient modulus model.

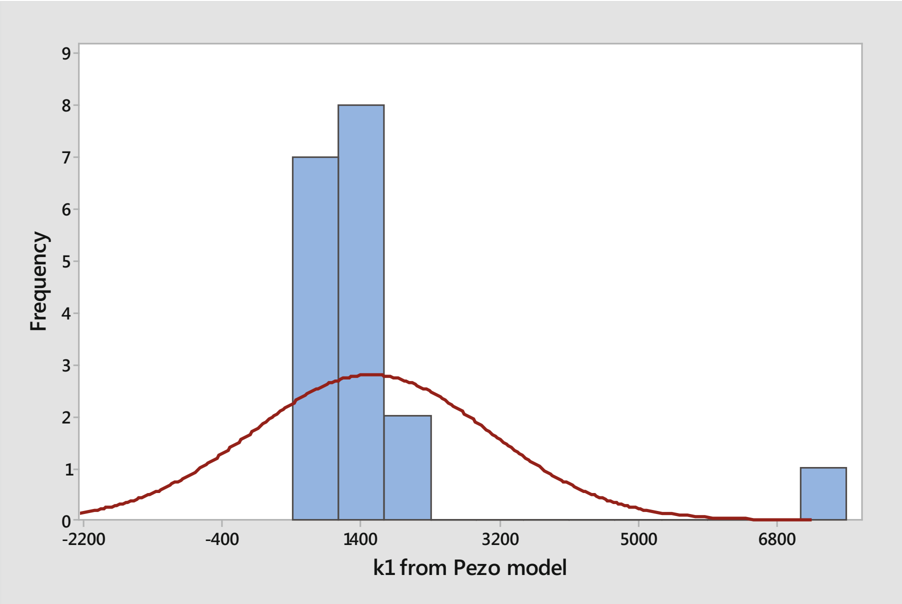


**Fig. 3a.** Histograms of Pezo's resilient modulus model parameters $k_1$

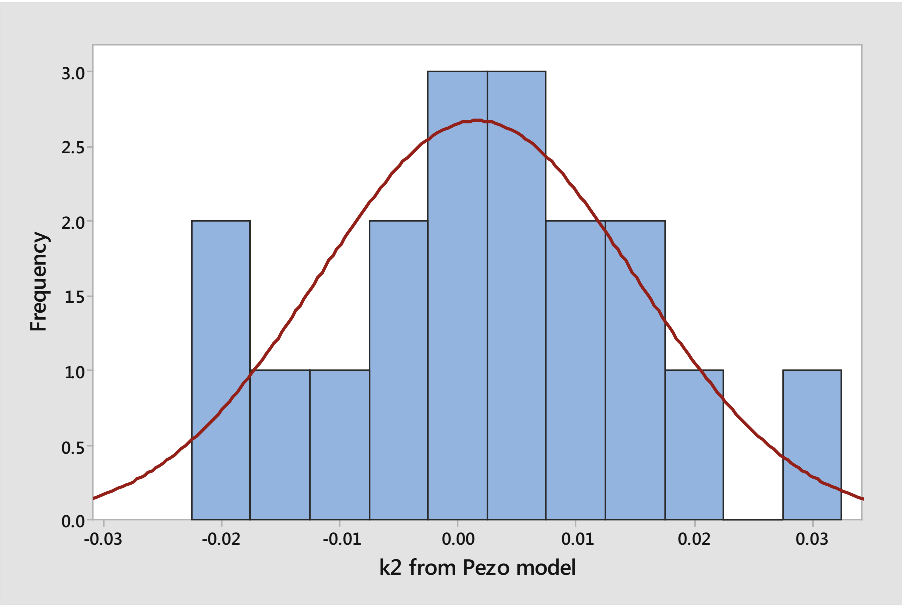


**Fig. 3b.** Histograms of Pezo's resilient modulus model parameters $k_2$

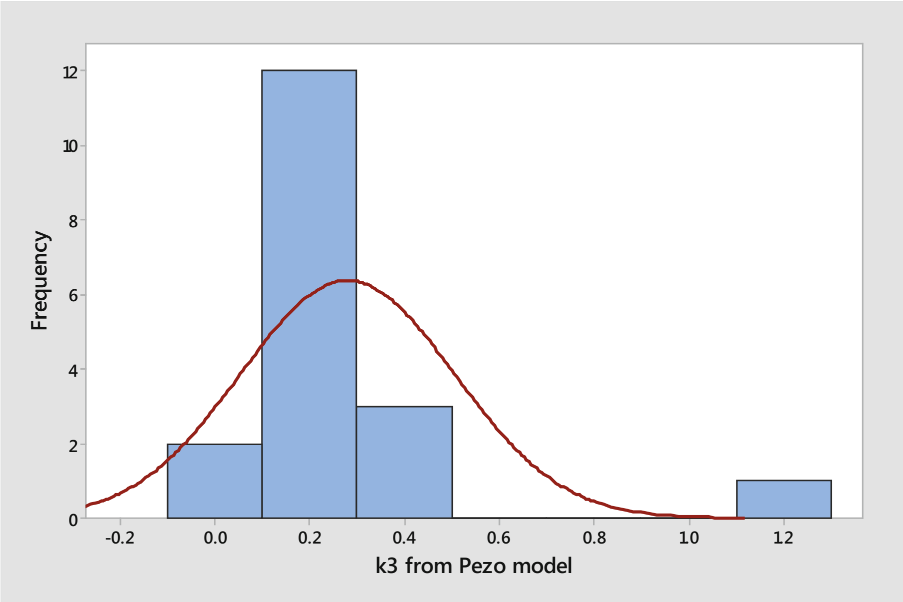


**Fig. 3c.** Histograms of Pezo's resilient modulus model parameters $k_3$

Figures 4a, 4b and 4c present the histogram of the resilient modulus model parameters $k_i$ obtained using the Ni et al. resilient modulus model.

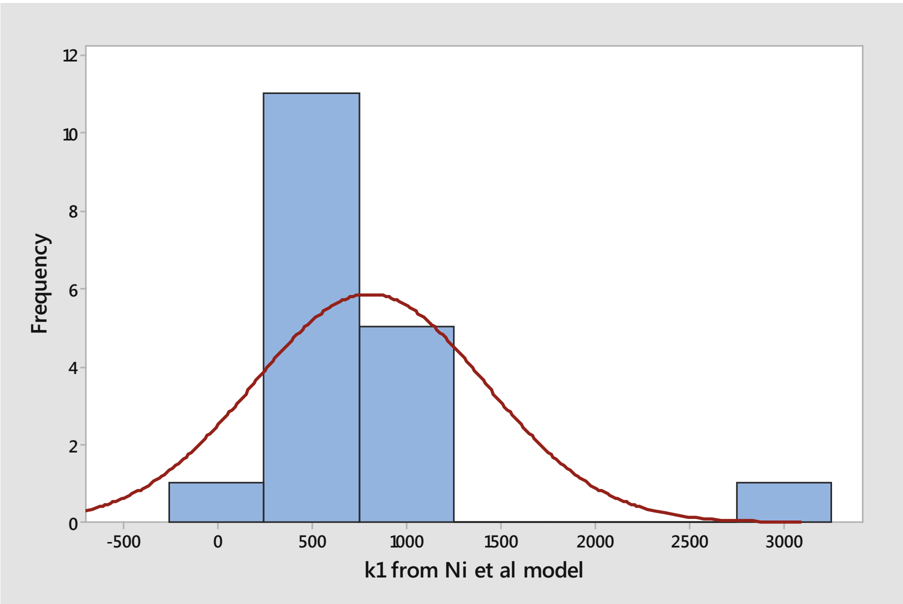


**Fig. 4a.** Histograms of Ni et al.'s resilient modulus model parameters $k_1$

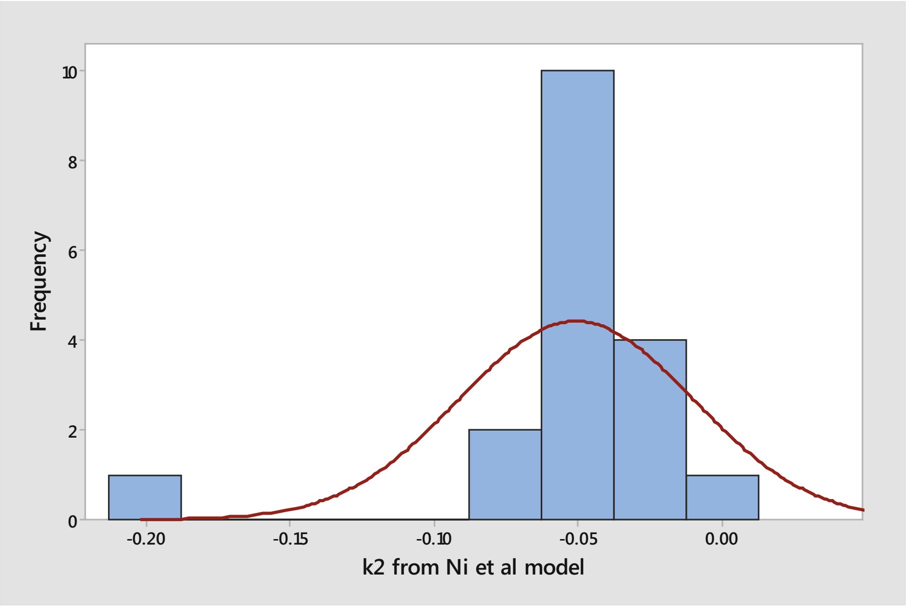


**Fig. 4b.** Histograms of Ni et al.'s resilient modulus model parameters $k_2$

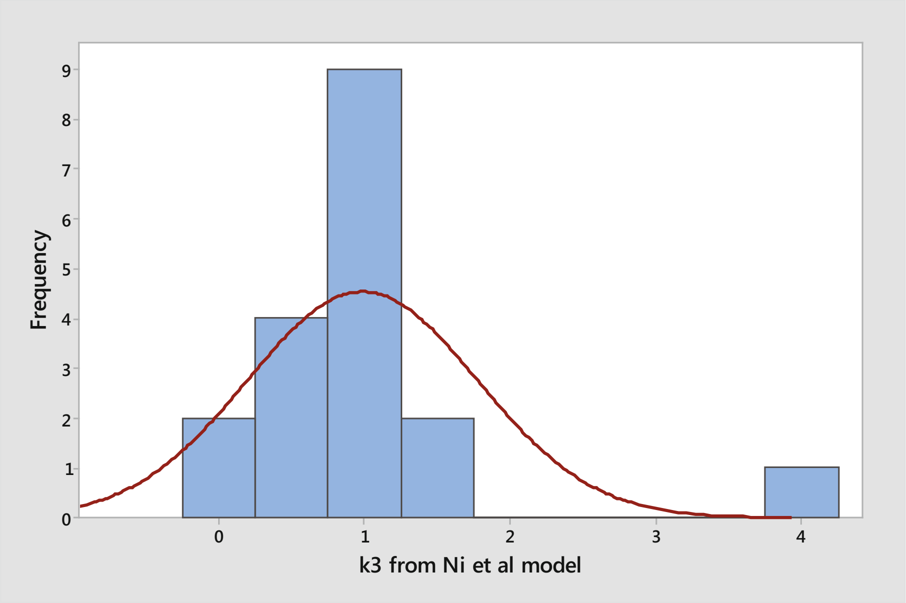


**Fig. 4c.** Histograms of Ni et al.'s resilient modulus model parameters $k_3$

Figures 5a, 5b and 5c present the histogram of the resilient modulus model parameters $k_i$ obtained using the Ooi et al. A resilient modulus model.

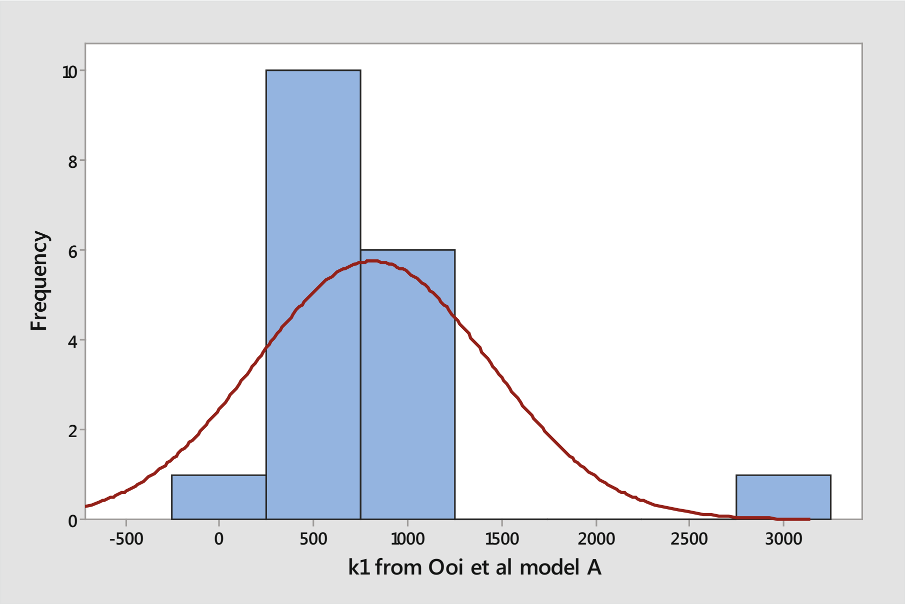


**Fig. 5a.** Histograms of Ooi et al. A resilient modulus model parameters $k_1$

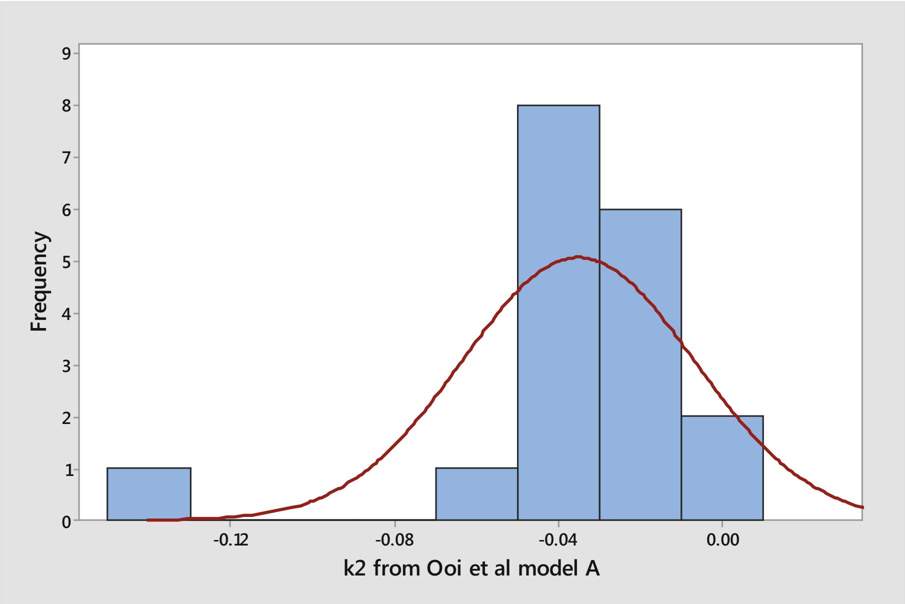


**Fig. 5b.** Histograms of Ooi et al. A resilient modulus model parameters $k_2$

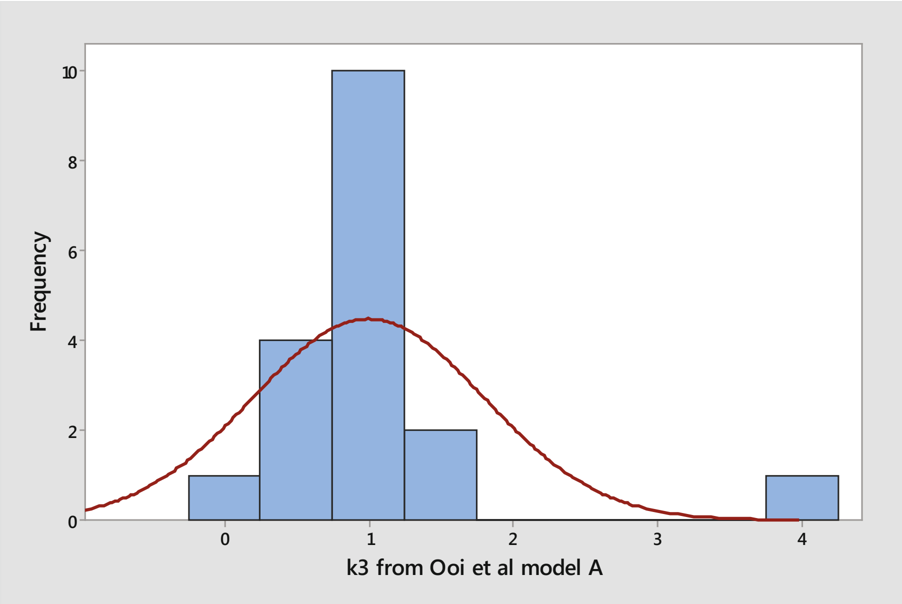


**Fig. 5c.** Histograms of Ooi et al. A resilient modulus model parameters $k_3$

Figures 6a, 6b and 6c present the histogram of the resilient modulus model parameters $k_i$ obtained using the Ooi et al. B resilient modulus model.

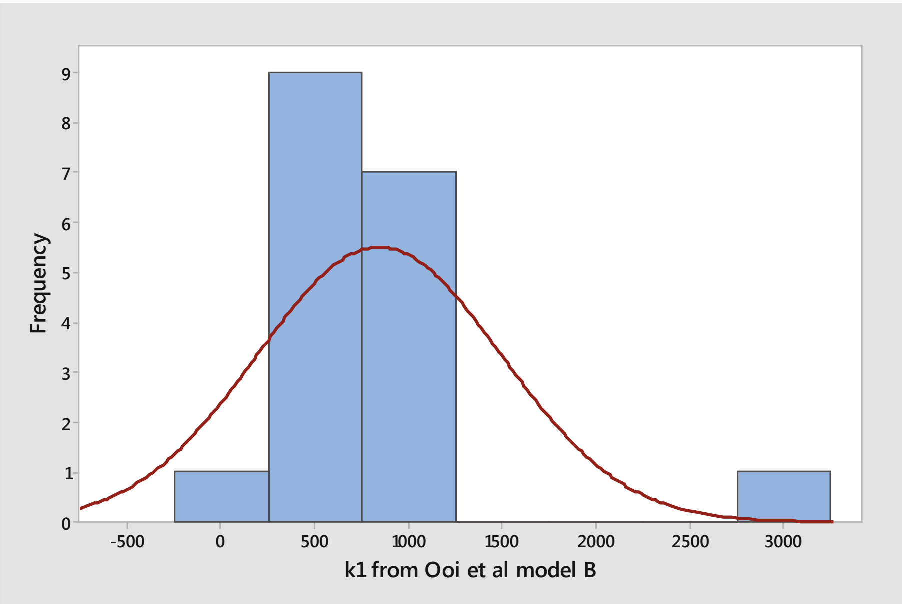


**Fig. 6a.** Histograms of Ooi et al. B resilient modulus model parameters $k_1$

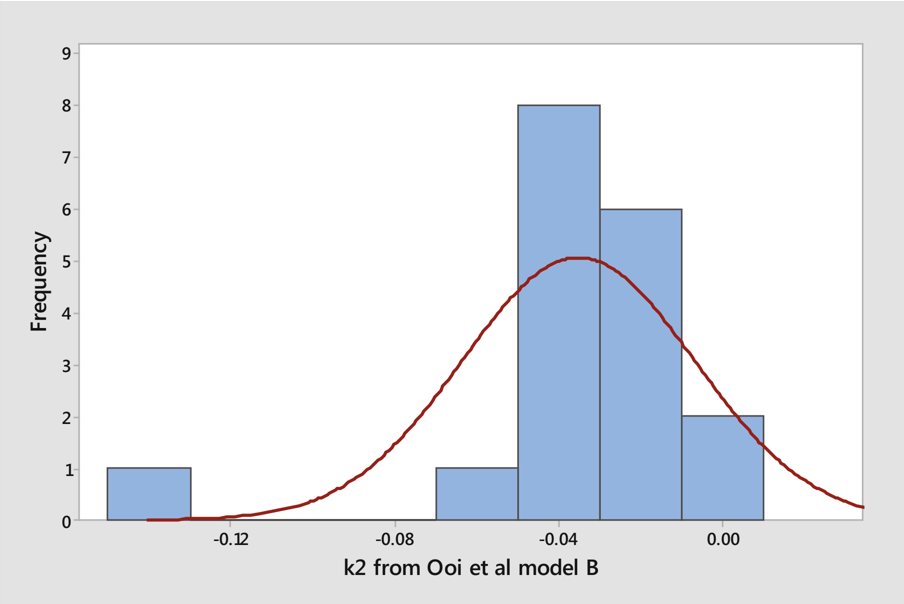


**Fig. 6b.** Histograms of Ooi et al. B resilient modulus model parameters $k_2$

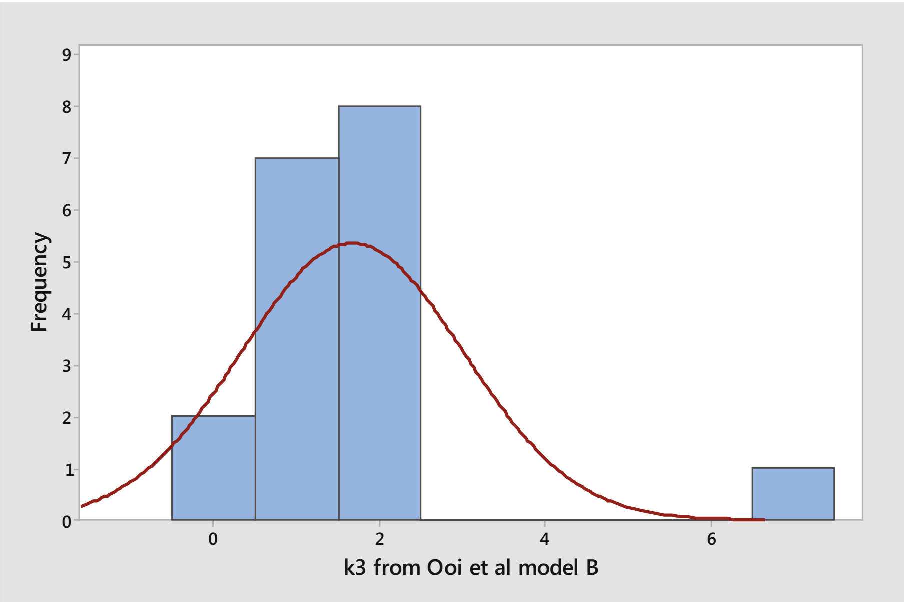


**Fig. 6c.** Histograms of Ooi et al. B resilient modulus model parameters $k_3$

Figures 7a, 7b and 7c present the histogram of the resilient modulus model parameters $k_i$ obtained using the NCHRP's resilient modulus model.

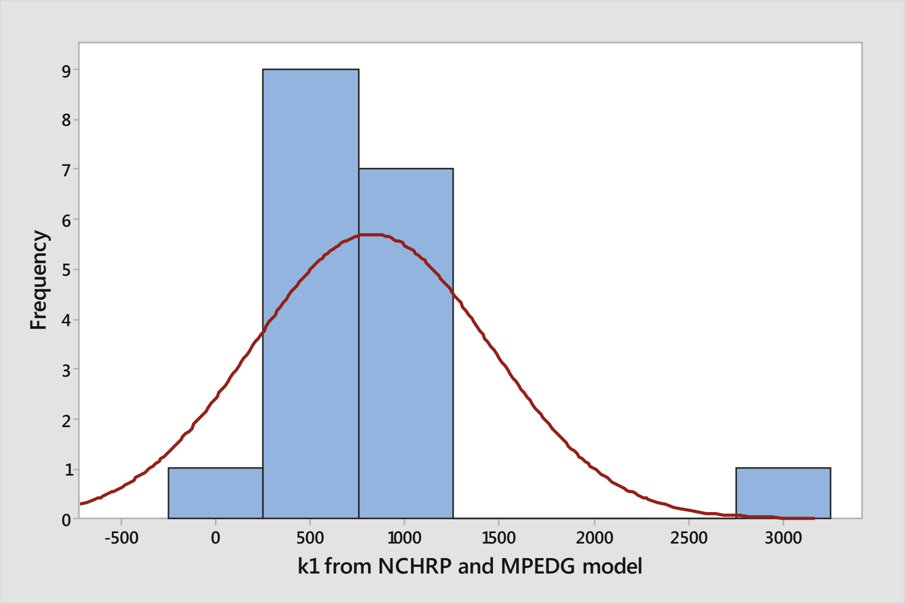


**Fig. 7a.** Histograms of NCHRP resilient modulus model parameters $k_1$

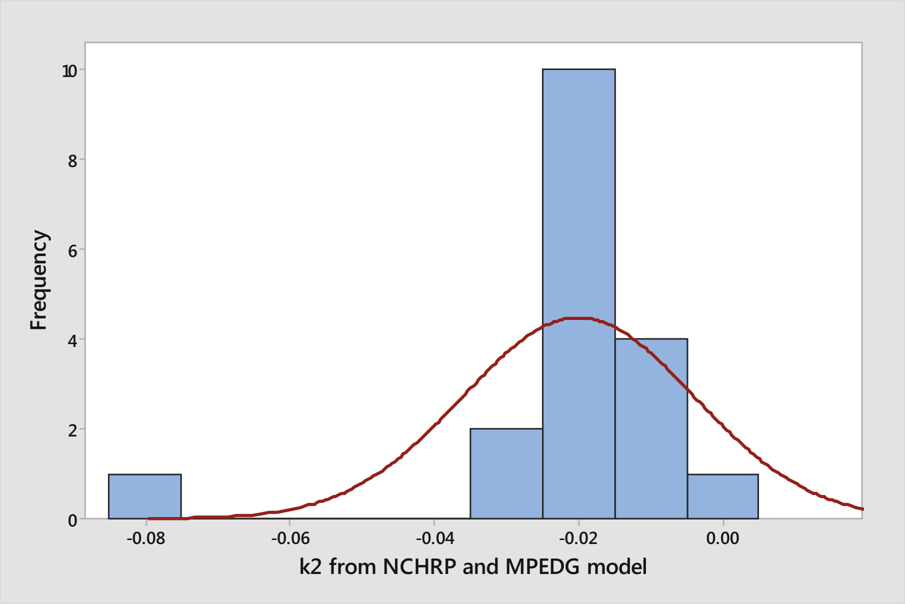


**Fig. 7b.** Histograms of NCHRP resilient modulus model parameters $k_2$

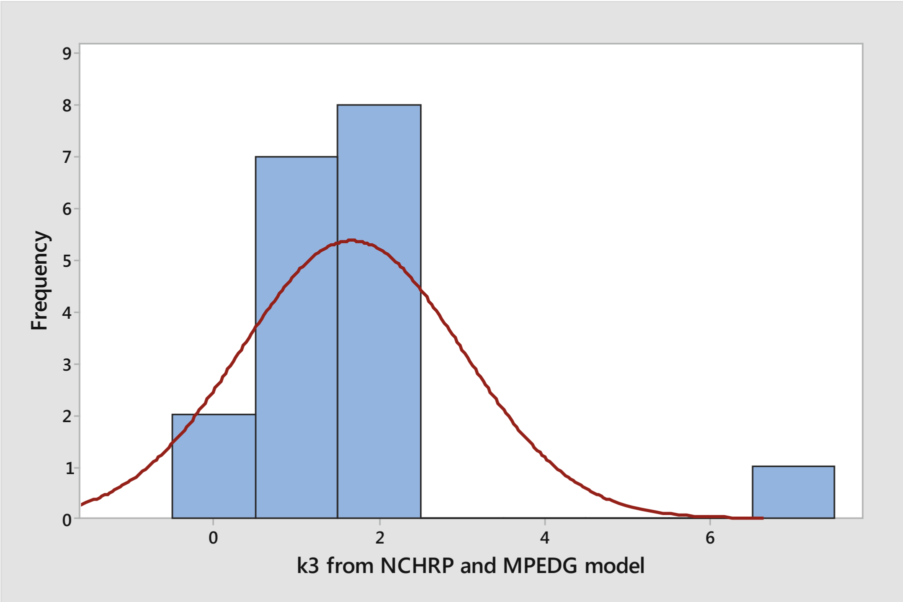


**Fig. 7c.** Histograms of NCHRP resilient modulus model parameters $k_3$

**Table 1.** Statistical data of $k_i$ obtained from the test results of the coarse-grained soils using resilient modulus models.

| S/No. | Model | Resilient modulus model parameters | A-1-b | A-2-4 | A-2-7 |
|---|---|---|---|---|---|
| 1 | Uzan 1985 | $k_1$ | 1128.2647 | 1567.4997 | 1493.3910 |
| | | $k_2$ | 7.98E-17 | 5.31E-17 | −4.1E-17 |
| | | $k_3$ | 0.2695 | 0.3094 | 0.2140 |
| 2 | Witczak and Uzan 1988 | $k_1$ | 1381.7457 | 2011.3930 | 1769.3172 |
| | | $k_2$ | 8.88E-17 | 5.45E-17 | −4.2E-17 |
| | | $k_3$ | 0.2695 | 0.3094 | 0.2140 |
| 3 | Pezo 1993 | $k_1$ | 1128.2647 | 1567.4997 | 1493.3910 |
| | | $k_2$ | 8.67E-17 | 3.2E-17 | −3.4E-17 |
| | | $k_3$ | 0.2695 | 0.3094 | 0.2140 |
| 4 | Ooi et al. 2004 | $k_1$ | 601.3008 | 797.2932 | 907.2052 |
| | | $k_2$ | −0.0339 | −0.0389 | −0.0269 |
| | | $k_3$ | 0.9587 | 1.1006 | 0.7613 |
| 5 | Ooi et al. 2004 | $k_1$ | 620.7723 | 823.0154 | 929.3132 |
| | | $k_2$ | −0.0339 | −0.0389 | −0.0269 |
| | | $k_3$ | 1.6028 | 1.8400 | 1.2727 |
| 6 | Ni et al. 2002 | $k_1$ | 594.1272 | 787.8599 | 899.0481 |
| | | $k_2$ | −0.0485 | −0.0557 | −0.0385 |
| | | $k_3$ | 0.9457 | 1.0856 | 0.7509 |
| 7 | NCHRP 2008 | $k_1$ | 605.4392 | 802.7457 | 911.9080 |
| | | $k_2$ | −0.0192 | −0.0220 | −0.0152 |
| | | $k_3$ | 1.5964 | 1.8326 | 1.2676 |

From the evaluation, as presented in Figs. 1a, 1b, 1c, 2a, 2b, 2c, 3a, 3b, 3c, 4a, 4b, 4c, 5a, 5b, 5c, 6a, 6b, 6c, 7a, 7b and 7c, the resultant resilient modulus parameters of coarse-grained soils with the following classifications (A-1-b, A-2-4 and A-2-7) using the resilient modulus models are as presented in Table 1.

Based on the evaluation of the resilient modulus equations for coarse-grained soils, it was observed from Table 1 for level 3 analysis that the resilient modulus equation adopted by NCHRP was the best in determining resilient modulus of coarse-grained soils.

## 4 Conclusion

Based on the results of this research, the following conclusions are reached:

1. Resilient modulus constitutive equation adopted by NCHRP and MEPDG was adopted for estimating resilient modulus of coarse-grained soils.
2. Default values of resilient modulus parameters was determined for coarse-grained soils as level 3 resilient modulus input.

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