# RESILIENT MODULUS OF Mn/ROAD SUBGRADE SOIL

Shongtao Dai

Office of Materials and Road Research
Minnesota Department of Transportation
1400 Gervais Avenue
Maplewood, MN 55109
USA
Tel: (651) 779-5218
Fax: (651) 779-5616
E-mail: shongtao.dai@dot.state.mn.us

John Zollars

Office of Materials and Road Research
Minnesota Department of Transportation
1400 Gervais Avenue
Maplewood, MN 55109
USA
Tel: (651) 779-5520
Fax: (651) 779-5616
E-mail: john.zollars@dot.state.mn.us

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## ABSTRACT

Laboratory remolded subgrade soil samples have been widely used to study subgrade resilient modulus. But physical conditions, such as moisture content and density, of such specimens may not represent in-situ conditions very well. Therefore, AASHTO and the Long-Term Pavement Performance program (LTPP) have recommended that undisturbed thin-walled tube samples should be used to study subgrade resilient behavior. The Minnesota Department of Transportation (Mn/DOT) is developing mechanistic-empirical pavement design approaches through the Minnesota Road Research project and has realized the importance of resilient modulus in the design approaches. Currently, the Mn/DOT is making an effort to study resilient modulus of unbound pavement materials through laboratory experiments. Under a research project at the Mn/DOT, several thin-walled tube samples of subgrade soil were obtained from six different pavement sections at the Minnesota Road Research project. Repeated loading triaxial tests were conducted on the soil specimens to determine resilient modulus at the Mn/DOT laboratory. Also, some soil properties, such as resistance R-value and plasticity index were obtained. R-value is an indicative value of performance when soil is placed in the subgrade of a road subjected to traffic. Two constitutive models (Uzan-Witczak universal model and the deviator stress model) were applied to describe the resilient modulus. The objective of the research was to compare these two well-known constitutive models in describing subgrade soil resilient behavior and to study effects of material properties on the resilient modulus.

From the specimens tested, the experimental results showed that the universal model described the subgrade resilient modulus slightly better than the deviator stress model and the coefficients in these two constitutive models were found to have correlation to material properties. Also, no well-defined relationships between R-value and the coefficients in the constitutive models were observed from the results of the tested specimens.

## INTRODUCTION

Subgrade soil stiffness is an important factor in pavement design. In recent years, mechanistic-empirical design approaches have attracted the attention of pavement engineers and researchers. The approaches require knowledge of mechanical properties of the materials comprising the pavement structure. Resilient modulus (Mr) has become a well-known parameter to characterize unbound pavement materials since a large amount of evidence has shown that the elastic (resilient) pavement deflection possesses a better correlation to field performance than the total pavement deflection *(1)*. Also, the 1993 AASHTO pavement design guide recommends using resilient modulus as a method to evaluate subgrade support.

Laboratory experiments have shown that resilient modulus of fine-grained cohesive soil is affected by stress level and is non-linearly related to stress. Several models have been proposed to describe the stress-dependent behavior of resilient modulus. Seed et al. *(2)* illustrated that the resilient modulus was linearly related to the logarithmic value of deviator stress, while Robnett and Thompson *(3)* showed the resilient modulus could be described by a bilinear function of applied deviator stress. Recently, a “universal” model was developed by Witczak and Uzan *(4, 5, 6)* to describe resilient modulus of all unbound (fine- and coarse- grained) materials. In the universal model, the resilient modulus is a function of both deviator stress and bulk stress. Therefore, this model considers the dilation effect of the materials. Furthermore, resilient modulus is greatly affected by the physical properties of the materials, such as moisture content, density and plasticity index, among others *(7,8,9)*. Elfino and Davidson *(10)* reported that there was up to forty-one percent variation in resilient modulus values obtained from soils at different water contents. Also, sample disturbance will influence the resilient modulus *(11)*. Therefore, characterization of resilient modulus using undisturbed subgrade soil samples may be more appropriate than using disturbed samples for studying pavement response.

In this study, a series of thin-walled tube samples of subgrade soil were taken at the Minnesota Road Research project (Mn/ROAD). The resilient modulus of the subgrade soils was obtained through confined triaxial tests. Also, moisture content, density, R-value and other material properties were determined. Two constitutive models (the universal model and the deviator stress model) were applied to describe the resilient modulus.

## EXPERIMENTS

In May of 1997, thin-walled tube samples of subgrade soil were obtained from five conventional flexible pavements with different structure designs and one aggregate surface pavement at the Mn/ROAD project. During the sampling process, care was taken to preserve in-situ subgrade samples. First, the asphalt concrete surface was removed by drilling an approximately 254 mm diameter core. Then the base material was excavated. Finally, a thin-walled metal tube was pressed into the in-situ subgrade soil to obtain samples. The ends of the thin-walled tube containing the soil samples were immediately sealed using wax to prevent the soil from being disturbed and losing moisture during transport and storage.

The thin-walled tube samples were utilized to determine resilient modulus through laboratory experiments at the Mn/DOT. A closed-loop, servo-hydraulic and computer controlled material testing machine (Interlaken) was used to conduct triaxial cyclic loading tests. Fig. 1 shows the schematic of the testing apparatus. The soil specimen is placed on a porous stone disc seated on a lower aluminum platen. The lower platen is fixed on the center of the apparatus base unit. Another porous stone disc and an aluminum platen (top platen) rest on the top of the specimen; the top platen is connected to a load cell. The internal load cell was used as the feedback to control the applied cyclic load. The soil specimen was sealed with a rubber membrane and O-rings were used to seal the membrane to the top and lower platens to protect the specimen from confining pressure. Three LVDTs were mounted between two aluminum rings, which were attached on the middle portion of the specimen. The three LVDTs were equally spaced around the specimen to directly measure axial displacement of the middle portion of the specimen. The apparatus was placed inside a large pressure cell and the confining pressure was applied with a closed-loop and computer-controlled air valve that can provide the desired pressure.

The resilient modulus tests were performed in general accordance with the Strategic Highway Research Program (SHRP) Protocol P-46. During the preparation of specimen, the ends of the specimen were carefully trimmed in an effort to make the two ends as parallel as possible. In general, the diameter of the specimen was about 71 mm (2.8 inches) and the height was about 152 mm (6 inches).

Prior to the resilient modulus test, the weight and dimensions of each specimen were measured and moisture content was determined after each test. In order to assess moisture gradient in the specimen, the specimen was split at the mid-height and two soil samples were taken from each part: one from the inside of the part and the other from the edge. The four samples were then oven dried overnight to obtain moisture content individually. The average value of the four moisture contents was used as the moisture content of the specimen. After the determination of moisture content, each specimen was sent to the Soil Testing Laboratory at the Minnesota Department of Transportation to obtain its R-value. In addition, during the construction of the Mn/ROAD project, some physical properties of subgrade soils in each pavement section were measured. Table 1 gives the material properties of the test specimens.

TABLE 1. Material Property of Tested Subgrade Soil Specimens.

| Specimen No. | Pavement Section | Moisture Content | Dry Density ($kN/m^3$) | Saturation (%) | %passing #200 | PI | LL | R |
|---|---|---|---|---|---|---|---|---|
| 1 | 30 | 0.161 | 18.06 | 93.5 | 65.7 | 27.7 | 45.4 | 16.1 |
| 2 | 35 | 0.17 | 17.62 | 91.5 | 57.2 | 11.2 | 29.6 | 17.9 |
| 3 | 27 | 0.175 | 17.91 | 99.1 | 63.4 | 18.6 | 37.1 | 15.4 |
| 4 | 27 | 0.149 | 18.04 | 86.3 | 63.4 | 18.6 | 37.1 | 17.9 |
| 5 | 22 | 0.156 | 18.65 | 99.8 | 58.6 | 18.4 | 34.8 | 12.3 |
| 6 | 22 | 0.162 | 18.17 | 95.8 | 58.6 | 18.4 | 34.8 | 16.9 |
| 7 | 17 | 0.184 | 17.54 | 97.7 | 57.8 | 17.4 | 35.5 | 17.2 |
| 8 | 17 | 0.154 | 18.64 | 99.1 | 57.8 | 17.4 | 35.5 | 15.4 |
| 9 | 4 | 0.145 | 18.61 | 92.8 | 58.3 | 14.2 | 32.5 | 17.8 |
| 10 | 4 | 0.141 | 18.78 | 91.8 | 58.3 | 14.2 | 32.5 | 15.5 |

## EXPERIMENTAL RESULTS

### Comparison of Resilient Modulus Models

The obtained moduli are plotted against deviator stress and confining pressure. Fig. 2 shows the typical results of the obtained resilient modulus. The resilient modulus, in general, decreased as the applied deviator stress increased (Fig. 2a). Also, the modulus slightly increased with the confining pressure for a given deviator stress level, meaning that the resilient modulus may also be a function of bulk stress (Fig. 2b). Two stress-dependent models were applied to describe the relationship between the resilient modulus and the stress state. The first one is referred as the deviator stress model, which is given by

$$Mr = A\sigma_d^{N} \qquad (1)$$

where

$\sigma_d$ = deviator stress which is the difference between the principal stress ($\sigma_1$) and confining pressure ($\sigma_3$).

$A$, $N$ = regression constants.

The second model is the universal model *(4,5,6)*. In this model, resilient modulus is a function of both bulk stress and octahedral shear stress. Since this model incorporates the effects of both deviatoric and volumetric stresses on resilient modulus, the model is applicable for all unbound materials *(6)*. The universal model has the form

$$Mr = k_1 \theta^{k_2} \tau_{oct}^{k_3} \tag{2}$$

where $k_1$, $k_2$ and $k_3$ are regression constants; $\theta$ is bulk stress given by $\sigma_1+\sigma_2+\sigma_3=\sigma_1+2\sigma_3$ and $\tau_{oct}$ is the octahedral shear stress which is defined as

$$\tau_{oct} = \frac{1}{3}\sqrt{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_1-\sigma_3)^2} \tag{3}$$

Under the condition of triaxial confining pressure, $\sigma_2 = \sigma_3$. So, $\tau_{oct}$ is simply given by

$$\tau_{oct} = \frac{1}{3}\sqrt{2(\sigma_1-\sigma_3)^2} = \frac{\sqrt{2}}{3}\sigma_d \tag{4}$$

Combining equation (2) and (4), the universal model is simplified to the form:

$$Mr = k_4 \theta^{k_2} \sigma_d^{k_3} \tag{5}$$

where $k_4$ is a regression constant.

For each test, a set of resilient modulus values was normally obtained at different stress levels as shown in Fig. 2. Both models (equations 1 and 5) were applied to describe the resilient modulus values. Equations (1) and (5) were transformed to linear equations by utilizing logarithm on both sides of the equations. The linear regression analysis was performed and coefficient $A$, $N$ in equation (1) and $k_2$, $k_3$, $k_4$ in equation (5) were evaluated. Table 2 summarizes the obtained coefficients for each specimen. The developed models were then used to backcalculate the resilient modulus of each soil specimen under each stress condition. The calculated modulus was compared with the measured one through linear regression. Table 2 shows the $R^2$ value of the regression line obtained from the measured and the calculated resilient moduli for each tested specimen. It can be seen that the $R^2$ value gained from the universal model was higher than that from the deviator stress model. Also, Fig. 3 shows the relationship between the measured and the calculated resilient moduli of all specimens for both models. Again, linear regression indicated that $R^2$ value from the universal model was slightly higher than that from the deviator stress model, and the intercept of the regression line from the universal model was closer to zero than that from the deviator stress model. This suggests that the universal model describes the resilient modulus slightly better than the deviator stress model.

TABLE 2. Regression Coefficients in the Deviator Stress Model and the Universal Model.

| Sample No. | Deviator Stress Model | | | Universal Model | | | |
|---|---|---|---|---|---|---|---|
| | A | N | $r^2$ | k4 | k3 | k2 | $r^2$ |
| 1 | 51.2 | -0.345 | 0.913 | 38.5 | -0.382 | 0.122 | 0.95 |
| 2 | 211.5 | -0.2824 | 0.915 | 179.6 | -0.302 | 0.072 | 0.935 |
| 3 | 76.9 | -0.384 | 0.895 | 39.4 | -0.447 | 0.28 | 0.965 |
| 4 | 210.6 | -0.3316 | 0.954 | 165.2 | -0.36 | 0.102 | 0.986 |
| 5 | 356.3 | -0.223 | 0.816 | 251.4 | -0.261 | 0.146 | 0.952 |
| 6 | 259.7 | -0.369 | 0.913 | 254.3 | -0.373 | 0.0097 | 0.913 |
| 7 | 236.1 | -0.454 | 0.922 | 177.4 | -0.489 | 0.121 | 0.938 |
| 8 | 274.6 | -0.289 | 0.847 | 175 | -0.367 | 0.206 | 0.955 |
| 9 | 329.9 | -0.257 | 0.869 | 286.3 | -0.273 | 0.059 | 0.887 |
| 10 | 391.3 | -0.518 | 0.962 | 279 | -0.562 | 0.145 | 0.979 |

## R-Values and Resilient Modulus

As discussed above, after resilient modulus test, each specimen was sent to the Soil Testing Laboratory at the Minnesota Department of Transportation to determine the R-value. The obtained R-values are given in Table 1 and ranged from 12.3 to 17.9. An attempt was made to correlate R-value to the coefficients in the above resilient modulus models. Figs. 4 and 5 show the R-values versus parameters $A$, $N$, $k_2$, $k_3$, $k_4$. Generally, for the materials tested, no clear and well-defined relationships between the R-values and parameter $A$, $N$, $k_2$, $k_3$ and $k_4$ were observed.

## Relationship between Coefficients and Material Properties

Since the moisture content, weight and dimension of each specimen were measured, the dry density of each specimen could be calculated (see Table 1). Fig. 6 represents a relationship between the moisture content and dry density. It seemed that the dry density decreased as the moisture content increased. The data values were below the values of the zero void curve and the saturation level ranged from 86.3% to 99.8%. Furthermore, the multiple regression analysis using the software SYSTAT was conducted to obtain relationships between coefficient $A$, $N$, $k2$, $k3$, $k4$ and the material properties. For the specimens tested, the following equations and corresponding regression results (R squared) were obtained

$$A = 2866.1 - 38.1*\left(\frac{Den}{PI}\right)^3 - 4382.9*\omega + 4.49*PI - 24.35*\lambda - 13.82*LL \qquad R^2=0.924 \qquad (6)$$

$$N = 62.68 - 15.68*Den^{0.5} - 113.3*\omega^{1.5} - 0.006*PI + 0.118*S \qquad R^2=0.711 \qquad (7)$$

$$k_4 = 5770.8 - 520.98*Den^{0.5} - 3941.8*\omega^{0.5} + 33.1*PI - 36.62*LL - 17.93*\lambda \qquad R^2=0.920 \qquad (8)$$

$$k_3 = 409.9 - 306.18*Den^{0.1} - 82.63*\omega + 0.033*PI + 0.138*S - 0.041*LL \qquad R^2=0.701 \qquad (9)$$

$$k_2 = -5.334 + 0.000316*Den^3 + 9.686*\omega - 0.054*PI + 0.046*LL + 0.022*\lambda \qquad R^2=0.871 \qquad (10)$$

where

Den = dry density of soil specimen.
$\omega$ = moisture content.
PI = plasticity index.
LL = liquid limit.
$\lambda$ = percentage of materials passing #200 sieve.

It can be seen that the coefficients $A$ and $k_4$ have higher $R^2$ values than the other coefficients, meaning that these two coefficients have better correlation with the material properties than the other coefficients. The above relationships could possibly be improved if some other material properties, such as clay content and percentage of organic carbon etc, were included. Furthermore, the obtained equations (6)-(10) were then used to calculate $A$, $N$, $k_2$, $k_3$ and $k_4$ from actual material properties given in Table 1 and the calculated values were compared with the actual coefficient values (Figs. 7 and 8). Again, coefficients $A$ and $k_4$ were better related to the material properties than the other coefficients. Additionally, the experimental results showed that between these two constitutive models, $A$ had a relationship with $k_4$ and $N$ was related to $k_3$. Figs. 9 and 10 show the relationships, respectively and indicate that the parameter $k_4$ and $k_3$ in the universal model may be estimated from parameter $A$ and $N$ in the deviator stress model.

## SUMMARY AND CONCLUSION

Thin-walled tube samples of subgrade soil were obtained from six different pavement sections at the MnROAD project. Triaxial cyclic loading tests were performed on the soil samples to determine resilient modulus. In the experiments, internal LVDTs and an interal load cell were used to measure specimen displacement and to control cyclic load, respectively. Other soil properties, such as R-value and plasticity index, were also obtained. Two constitutive models, the universal model and the deviator stress model, describing relationships between resilient modulus and stress state were applied to characterize the experimental data.

On the basis of the experimental data from the tested materials, the results showed that the universal model described the resilient modulus slightly better than the deviator stress model. The coefficients in the both models were found to depend on the material properties. Coefficient $A$ in the deviator stress model and $k_4$ in the universal model had better correlation to the material properties than the other coefficients in the models. Also, it appeared that coefficient $A$ in the deviator stress model was related to $k4$ in the universal model, and $N$ in the deviator stress model was correlated to $k3$ in the universal model. This suggests that parameter $k_4$ and $k_3$ in the universal model may be estimated from parameter $A$ and $N$ in the deviator stress model. The relationships presented in the paper are based on the limited experimental data. The relationships can be improved if more experimental data are included.

## ACKNOWLEDGMENTS

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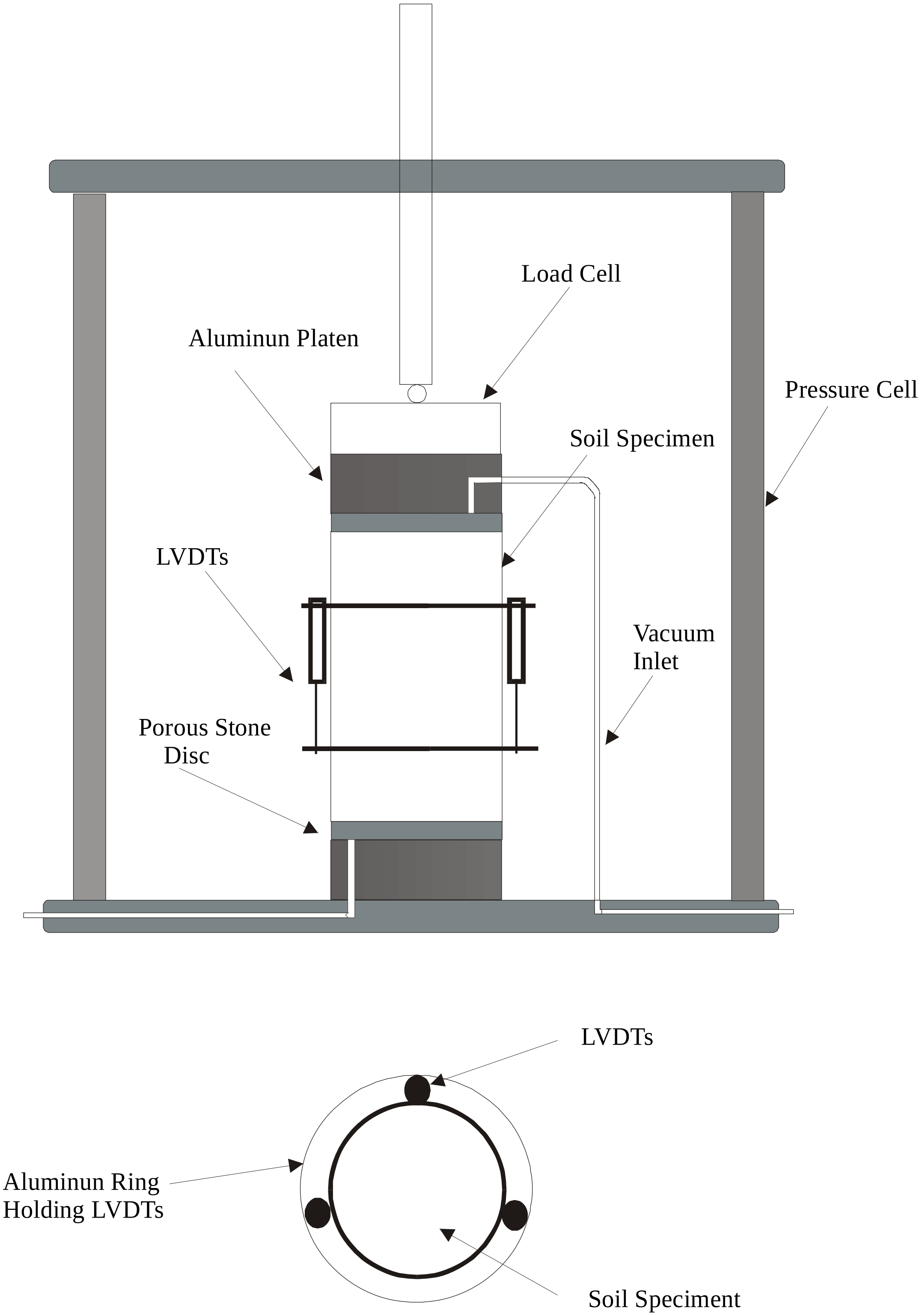
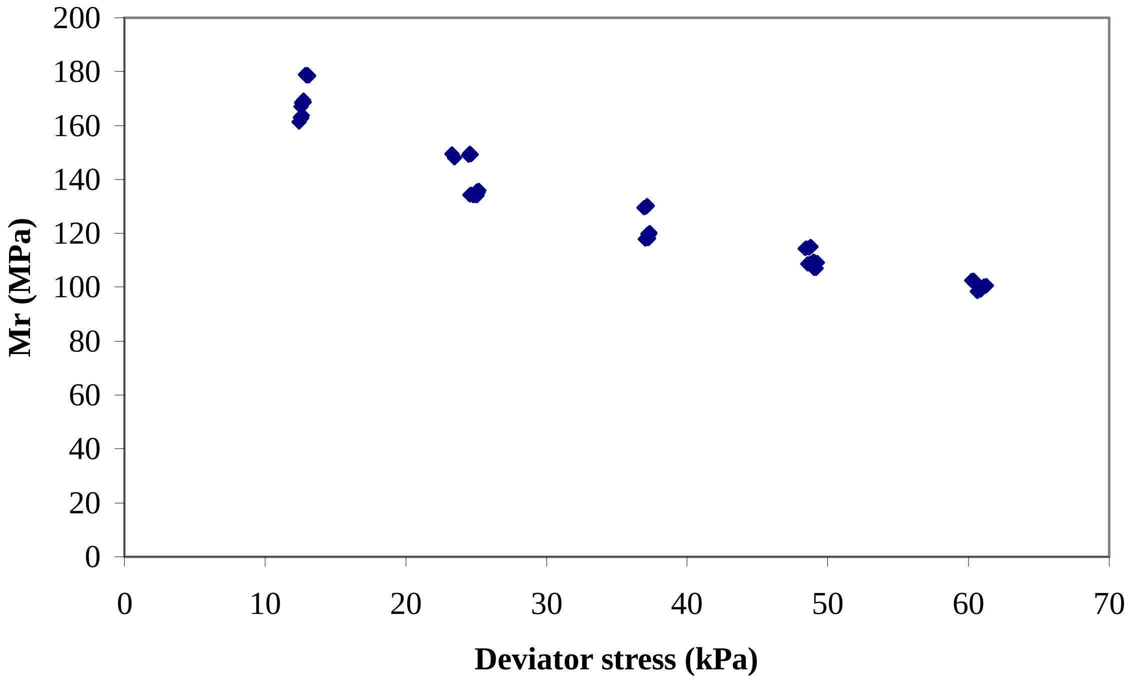
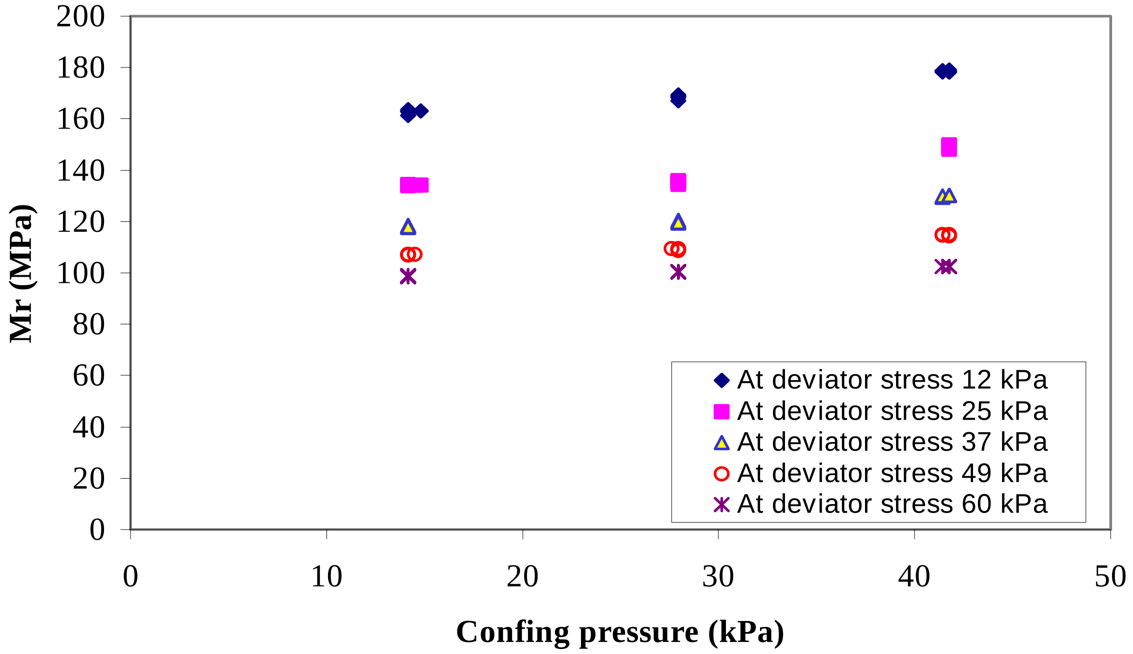


FIGURE 1 Schematic of resilient modulus testing apparatus.

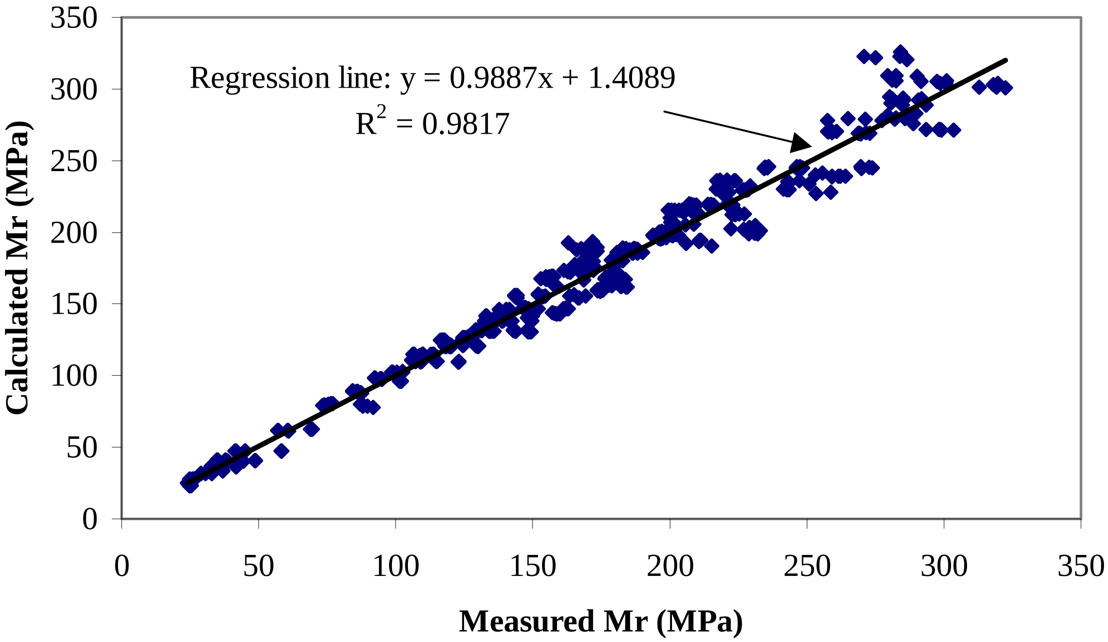


(a) Resilient modulus as a function of deviator stress.

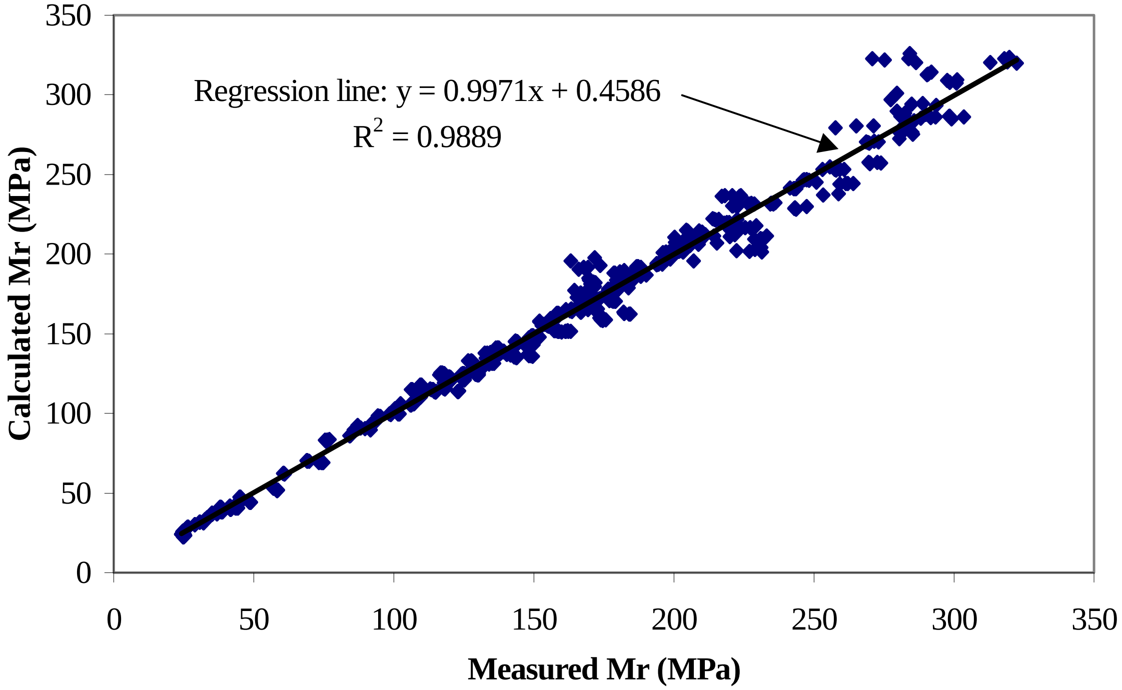


(b) Resilient modulus as a function of confining pressure at different deviator stress levels.

FIGURE 2 Typical relationships of resilient modulus with deviator stress and confining pressure.



(a) Resilient modulus from the deviator stress model.



(b) Resilient modulus from the universal model.

FIGURE 3 Comparison of measured resilient modulus with calculated resilient modulus obtained from the deviator stress model and the universal model.

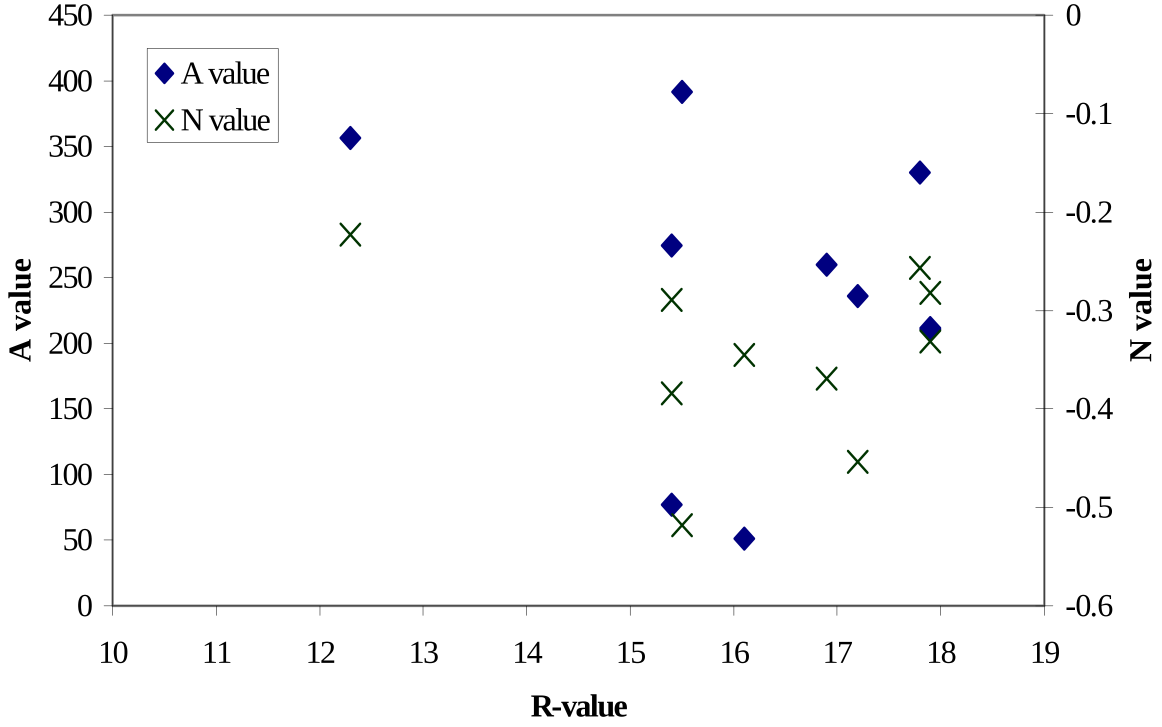
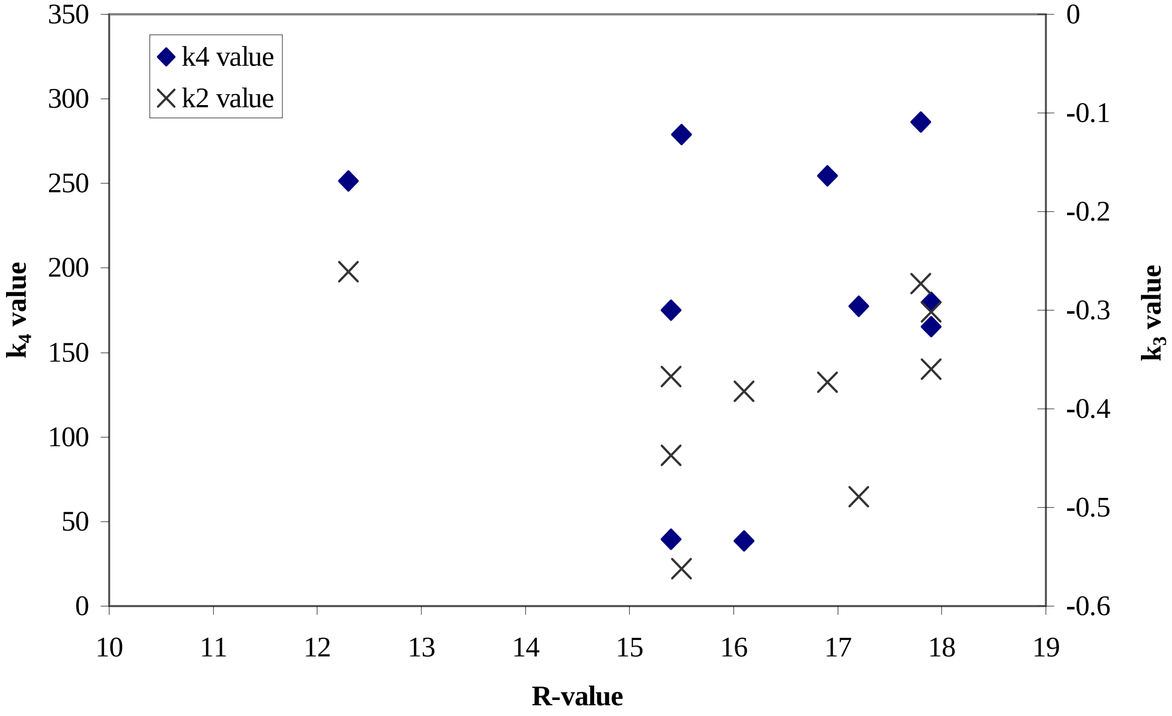
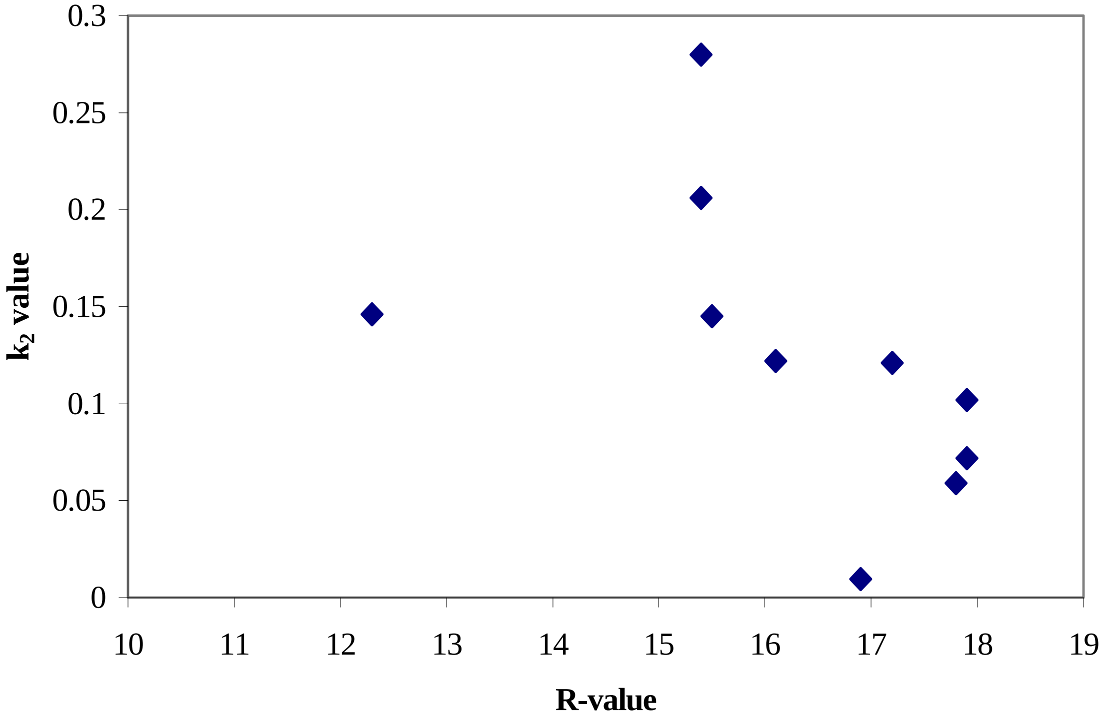


FIGURE 4 R-value versus values of the deviator stress model parameters *A* and *N*.



(a) R-value versus k3 and k4



(b) R-value versus k2

FIGURE 5 R-value versus values of the universal model parameters $k_4$, $k_3$ and $k_2$.

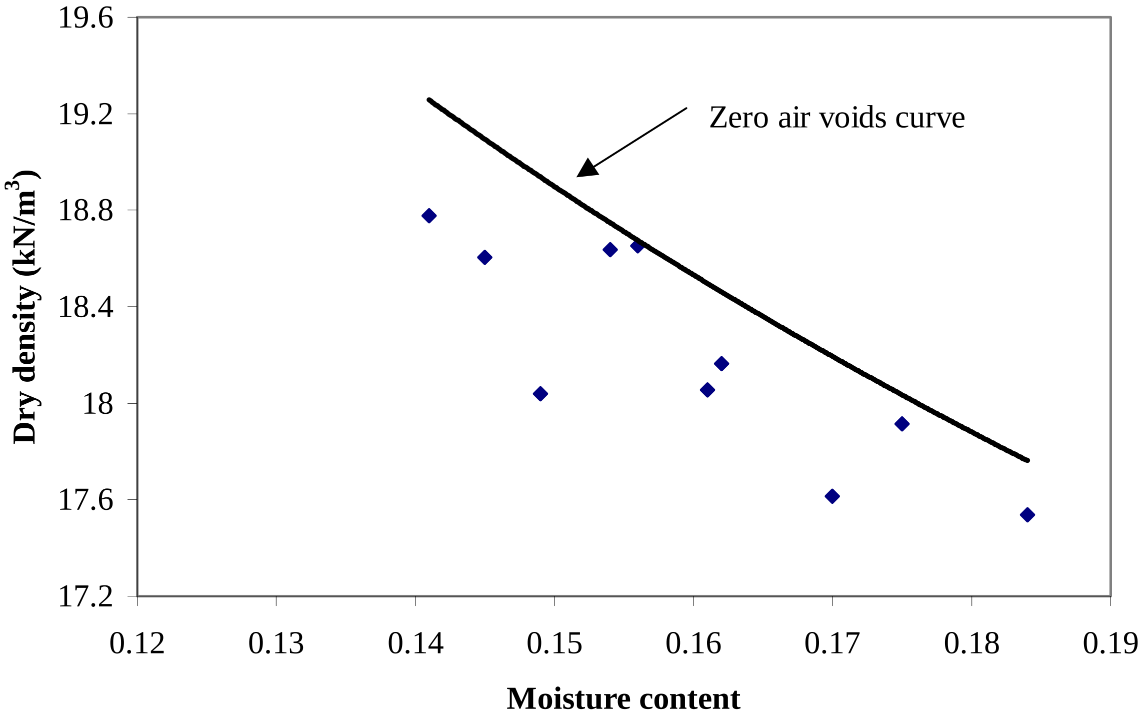
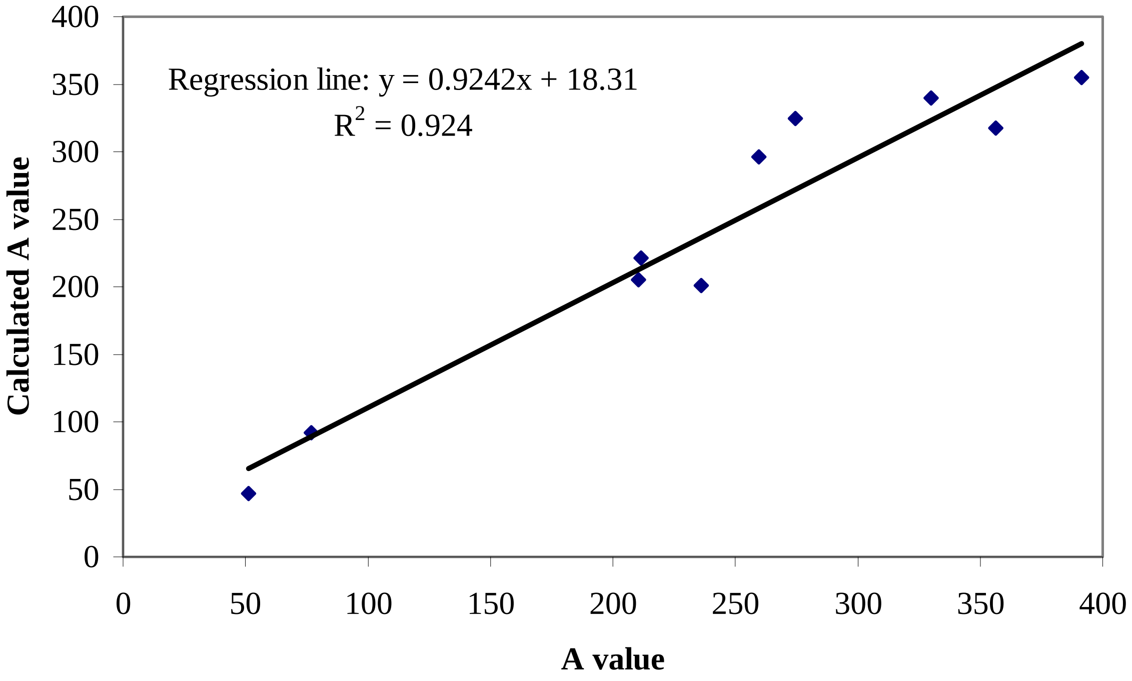


FIGURE 6 Relationship between in-situ moisture content and dry density.



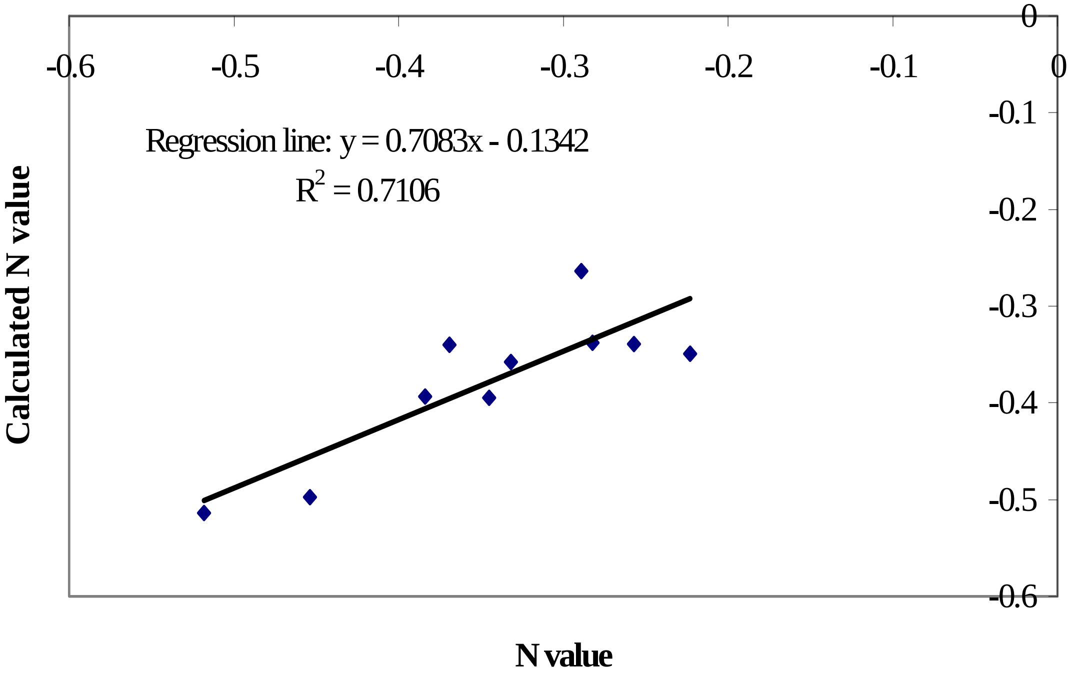
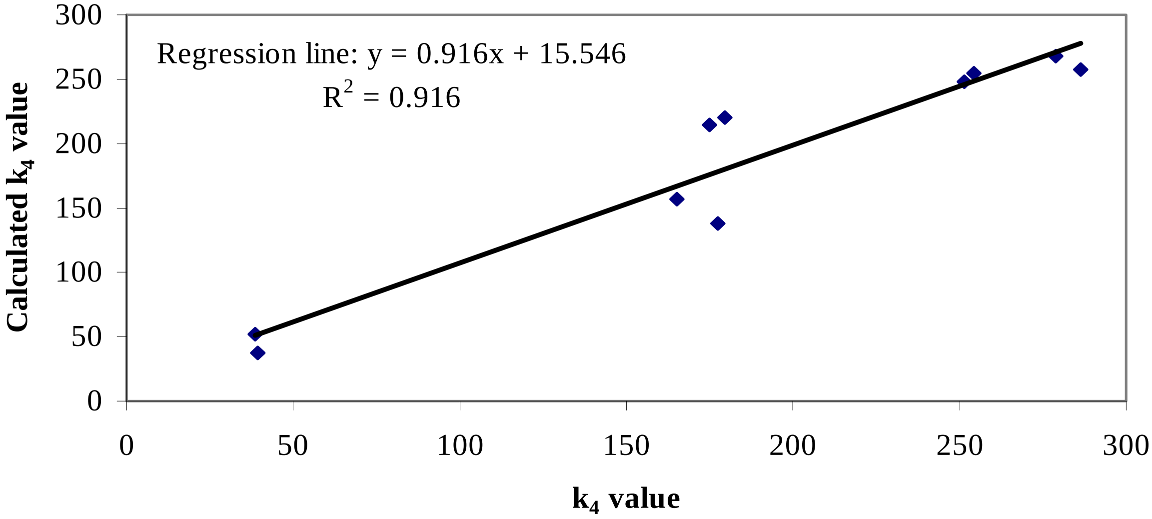
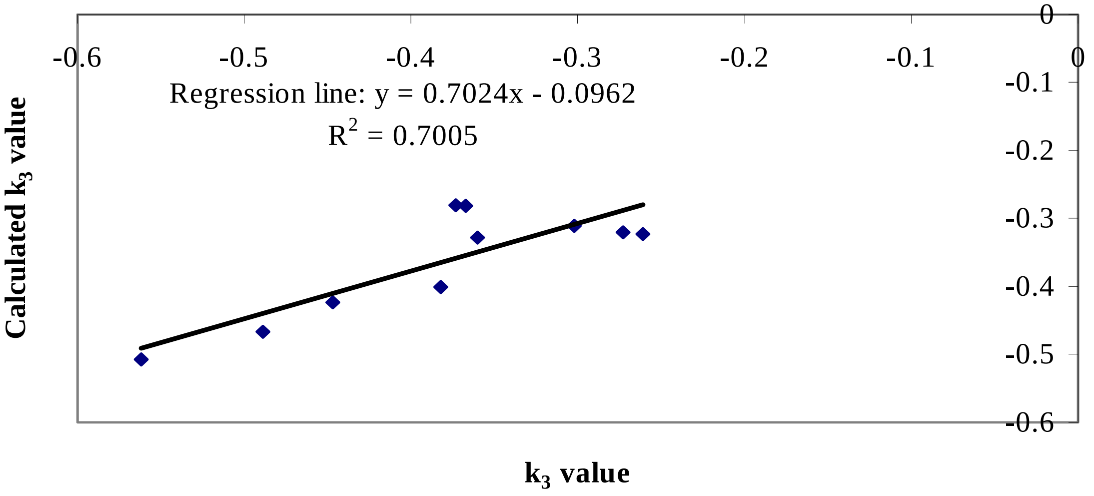


FIGURE 7 Comparison between *A* and *N* from experiments with calculated *A* and *N* values from equation (6) and (7).





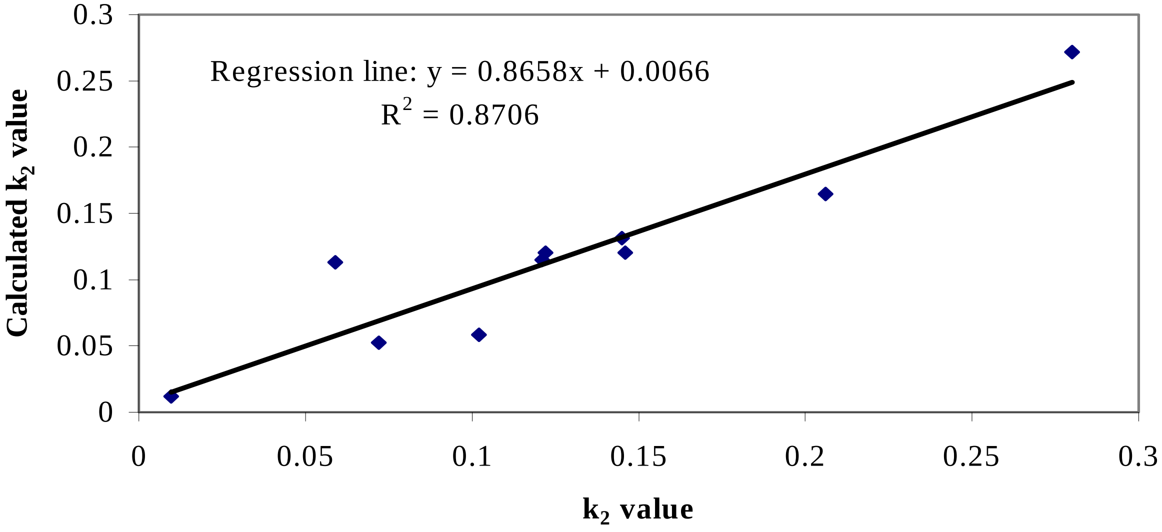


FIGURE 8 Comparison between $k_4$, $k_3$ and $k_2$ values obtained from experiments with calculated $k_4$, $k_3$ and $k_2$ from equation (8), (9) and (10)

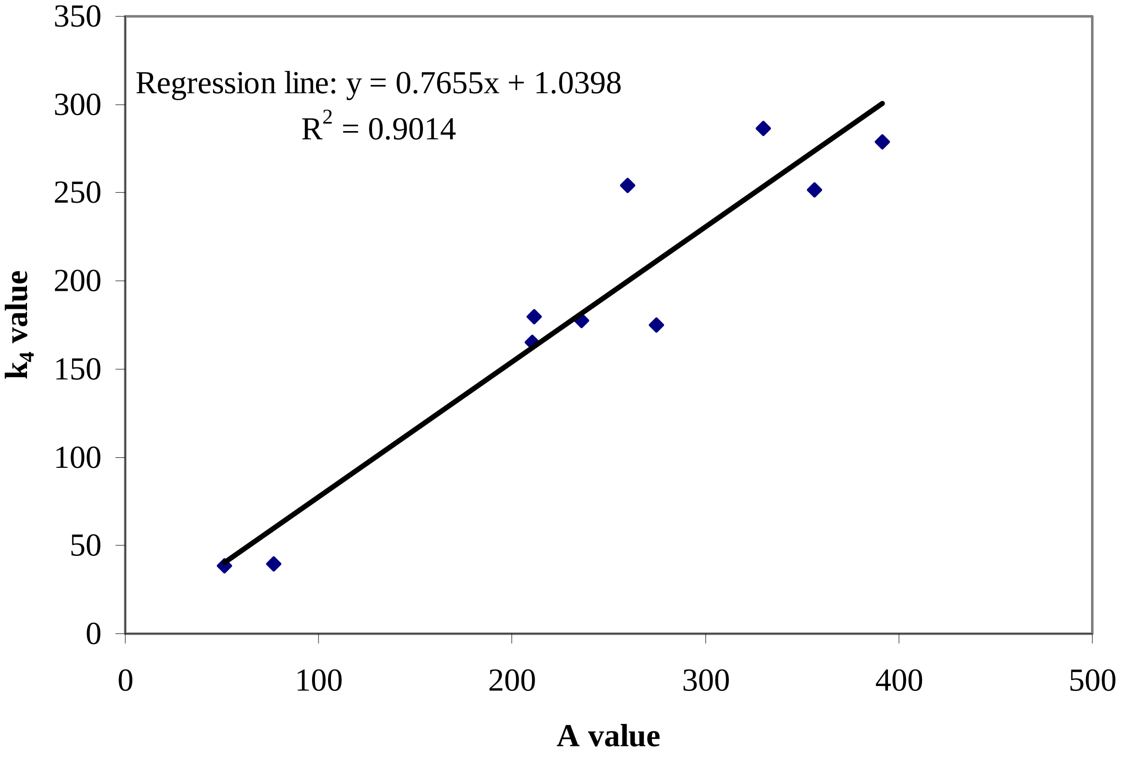


FIGURE 9 Relationship between *$k_4$* in the universal model and *A* in the deviator stress model.

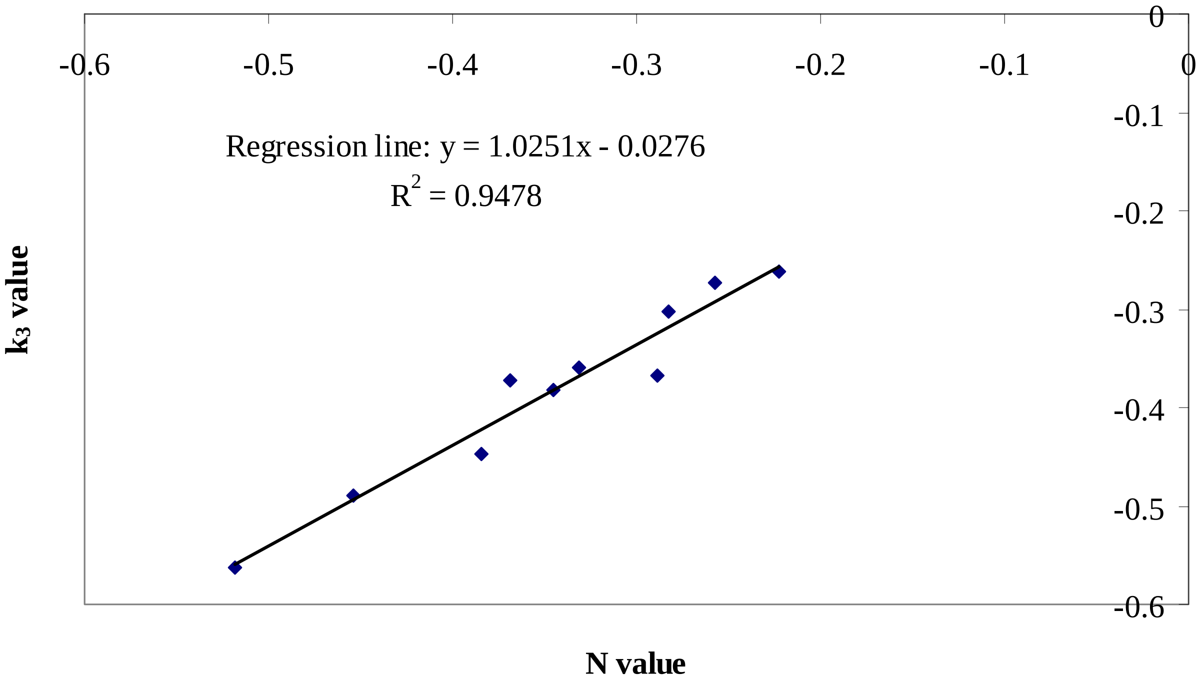


FIGURE 10 Relationship between $k_3$ in the universal model and *N* in the deviator stress model.