Repeated Static Loading Triaxial Tests for Determination of Resilient Properties of Sands

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The possibility of determining the resilient modulus of sand through repeated static loading triaxial test was investigated. Six different sands, with gradings ranging from very coarse to extremely fine, were tested. For each sand investigated, one triaxial specimen was prepared. Repeated static loading triaxial tests and cyclic loading triaxial tests were then carried out on the same specimen. Comparison of the resilient moduli obtained from both types of tests clearly showed the possibility of determining resilient moduli in relatively simple-to-perform, repeated static loading triaxial tests.

Mechanistic design procedures for asphalt pavements often use the resilient modulus M_R to characterize the elastic stiffness of the subgrade soil and materials in the unbound layers of the pavement. Some empirically based design procedures like the recently published AASHTO method (*1*) also use M_R to characterize elastic stiffness of unbound materials.

The test method most widely used for determination of the resilient modulus M_R is the cyclic loading triaxial test. In this test, cylindrical specimens of the material to be investigated are subjected to stresses that closely simulate in-situ stresses in the pavement, and the resulting deformations are measured. The tests are usually carried out at frequencies of 1 to 10 Hz. As complicated servo-hydraulic equipment is needed to apply the loading required at these frequencies, the cyclic loading triaxial test is not suited for routine application. This factor strongly inhibits the implementation of design procedures using the resilient modulus M_R as input.

A strong need therefore exists for development of simpler tests that still allow accurate determination of resilient moduli of unbound materials. This paper describes an investigation into the possibility of determining resilient moduli of sands through repeated static loading triaxial tests. If this possibility exists, simple pneumatic or even dead-load testing equipment can be used to determine M_R.

The research described in this paper is part of a major research project dealing with the structural contribution of unbound material layers to asphalt pavements (*2*). Full details of the research described here can be found in a recently published report (*3*).

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SANDS INVESTIGATED

The six sands investigated in this study represent the sands most widely used for road construction in the Netherlands. The names of the place of origin of the sands will be used in this paper to denote the sands.

The particle size distribution of the sands was determined by washing a sample through a 75 μm sieve. After the material retained was oven dried, a dry analysis was performed. The material passing the 75 μm sieve was subjected to a hydrometer analysis. The results of both the dry sieving and the hydrometer analyses were then combined to yield the particle size distribution of the sands (Figure 1). Using the data obtained in the particle size analysis, the sands were classified using the Extended Unified Soil Classification System (Table 1).

To obtain reference values for the moisture content and the dry density of the triaxial specimens, Proctor compaction tests were carried out on the sands, according to AASHTO T 180, method B (modified compaction level) (*4*). Table 1 shows the resulting values of the optimum moisture content w_{opt} and the maximum dry density $\rho_{d,max}$.

TRIAXIAL TEST PROCEDURES

Triaxial Test Apparatus

Figure 2 shows the schematics of the triaxial test apparatus used for this study. The specimen tested measures 100 mm in diameter and 200 mm in height. The constant confining stress is applied through air pressure in the plexiglass cell, while the deviator stress is applied by a servo-hydraulic actuator through the loading piston. A load cell is incorporated inside the triaxial cell, thereby eliminating load measuring errors caused by the friction between the loading piston and the top of the triaxial cell. Axial deformation of the triaxial specimen is measured by

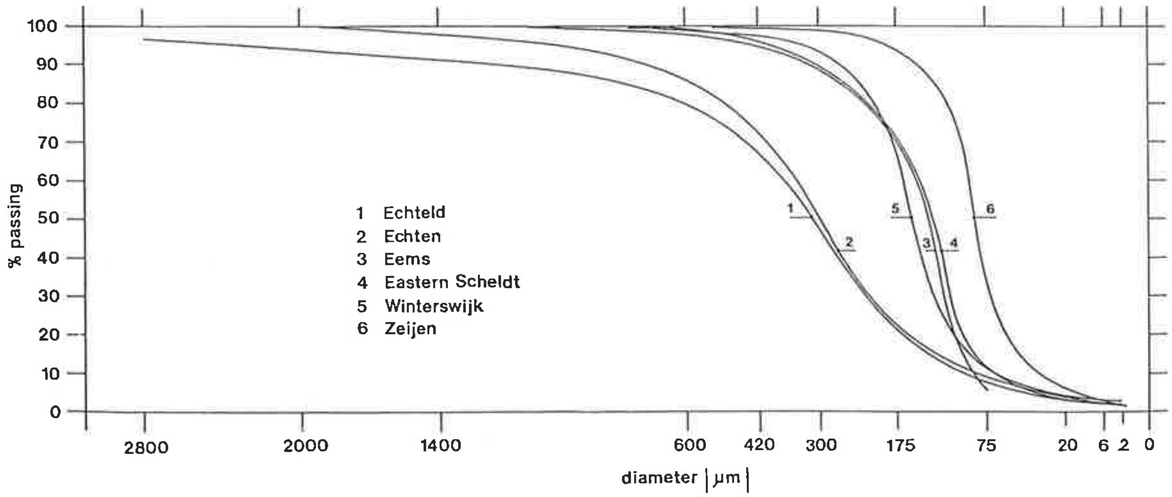

FIGURE 1 Particle size distribution of the sands investigated.

TABLE 1 CLASSIFICATION, PROCTOR, TRIAXIAL SPECIMEN, AND RESILIENT MODULI DATA FOR THE SIX SANDS INVESTIGATED

	Classification Extended USCS		Proctor		Triaxial Specimen		Resilient Modulus		
Sand	Type	Code	w_{opt} (%)	$\rho_{d,max}$ (kg/m^3)	w (%)	ρ_d (kg/m^3)	K_1 (MPa)	K_2 (-)	R^2 (-)
Echteld	Poorly graded sand	SP/SF	12.7	1,745	12.7	1,745	8.09	.56	.92
Echten	Poorly graded sand	SP/SF	13.7	1,712	13.8	1,711	7.64	.57	.96
Eems	Poorly graded sand	SP/SF	13.0	1,665	12.9	1,666	8.85	.56	.96
Eastern Scheldt	Poorly graded sand	SP/SF	15.7	1,668	15.8	1,667	9.80	.54	.92
Winterswijk	Poorly graded sand	SP/SF	10.5	1,697	10.5	1,698	10.53	.53	.96
Zeijen	Silty sand	SMF	15.0	1,593	15.1	1,592	9.74	.52	.96

an LVDT connected to the loading piston outside the triaxial cell. Radial deformation of the triaxial specimen can be measured by three noncontacting sensors, which are mounted through the plexiglass cell on a horizontal plane at half the specimen height.

Cyclic Loading Testing Procedure

Figure 3 shows the stresses applied to the triaxial specimen in the cyclic loading tests. The constant, all-around confining stress σ_3 simulates the constant overburden stress in road construction. The cyclic deviator stress σ_d simulates the in-situ vertical stress due to traffic loading. As shown in Figure 3, σ_d is cyclic, varying between zero and a preset value at a frequency of 1 Hz. The major principal stress σ_1 is then equal to $\sigma_1 = \sigma_d + \sigma_3$, and the intermediate principal stress is equal to the minor principal stress σ_3. The sum of principal stresses θ is equal to $\theta = \sigma_1 + \sigma_2 + \sigma_3 = \sigma_d + 3\ \sigma_3$.

Cyclic loading triaxial tests were carried out at several different combinations of the confining stress σ_3 and the deviator stress σ_d. Each triaxial specimen was tested at 29 different combinations of stresses: σ_3 ranging from 10 to 300 kPa and the stress ratio σ_1/σ_3 ranging from 2 to 6.

Static Loading Testing Procedure

In the static loading triaxial tests to determine the resilient modulus M_R, the procedure suggested by Kalcheff and Hicks (*5*) was followed. The procedure calls for a series of alternate load-on/load-off periods of 5 minutes, followed by a load-on period of 30 minutes (Figure 4). After this period, the axial load is removed and the resilient deformation $\varepsilon_{a,r}$ is measured. The resilient modulus M_R is then calculated as the ratio of the applied deviator stress over the axial resilient strain.

The repeated static loading testing procedure described above requires about one hour to perform for each selected combination of σ_3 and σ_d. As M_R has to be determined for a number of stress ratios, owing to the stress-dependent nature of M_R, this procedure is far too time-consuming for routine application. Therefore, the resilient deformation of the triaxial specimen was also measured after the first load-on period of 5 minutes (Figure 4), to check the possibility of using this strain value for accurate determination of M_R.

Because of the time-consuming nature of the repeate static loading tests, only 10 different combinations of σ_3 and σ_d were used in these tests; σ_3 ranged from 10 to 200 kPa and σ_1/σ_3 ranged from 2 to 4.

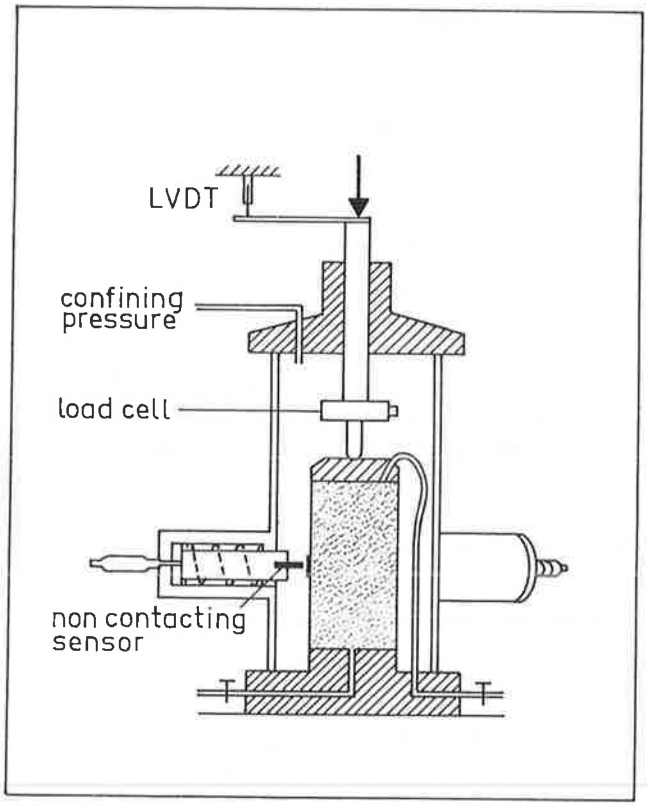

FIGURE 2 Schematics of triaxial test apparatus.

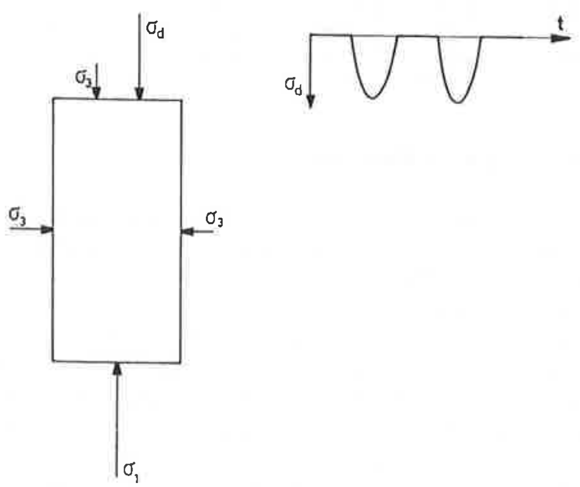

FIGURE 3 Stresses applied to triaxial specimen in cyclic loading tests.

Test Sequence

The cyclic loading and repeated static loading tests for determining M_R were carried out on the same specimen. One triaxial specimen was prepared for each of the sands investigated. At each confining stress level, the repeated static loading tests were carried out first, followed by the cyclic loading tests at the confining stress level. Before actual testing, the triaxial specimen was subjected to several hundred load applications at a small stress ratio to assure a proper seating between the specimen and the loading caps.

Specimen Preparation

The triaxial specimens were prepared in six layers, using a split-mold and a tamping device. The optimum moisture content and the maximum dry density from the modified Proctor compaction tests served as target values for the triaxial specimens. The values obtained for moisture content and dry density of the triaxial specimens are shown in Table 1. Comparison of the target values and the actual specimen values for moisture content and dry density reveals very little deviation.

CYCLIC LOADING TEST RESULTS

The cyclic loading triaxial tests for determining the resilient modulus M_R were carried out at 29 different combinations of stresses. For each stress combination, the axial resilient strain of the specimen was determined, and the resilient modulus M_R was calculated according to

$$M_R = \frac{\sigma_d}{\varepsilon_{a,r}} \quad (1)$$

where

M_R = resilient modulus (MPa),
σ_d = deviator stress (MPa), and
$\varepsilon_{a,r}$ = axial resilient strain (–).

Figure 5 shows the results of the cyclic loading tests for the Echteld sand. The obtained 29 values of the resilient modulus M_R have been plotted in Figure 5 against the sum of principal stresses θ. The relationship between M_R and θ as shown in Figure 5 can be described by the well-known equation:

$$M_R = K_1\left(\frac{\theta}{\theta_0}\right)^{K_2} \quad (2)$$

where

M_R = resilient modulus (MPa),
θ = sum of principal stresses (MPa),
θ_0 = reference stress 1 MPa (MPa),
K_1 = material parameter (MPA), and
K_2 = material parameter (–).

The division of θ by the reference stress θ_0 is done for purely mathematical reasons, i.e., rendering the stress parameter in equation 2 dimensionless.

The values of the material parameters K_1 and K_2 for the Echteld sand are shown in Figure 5, together with the

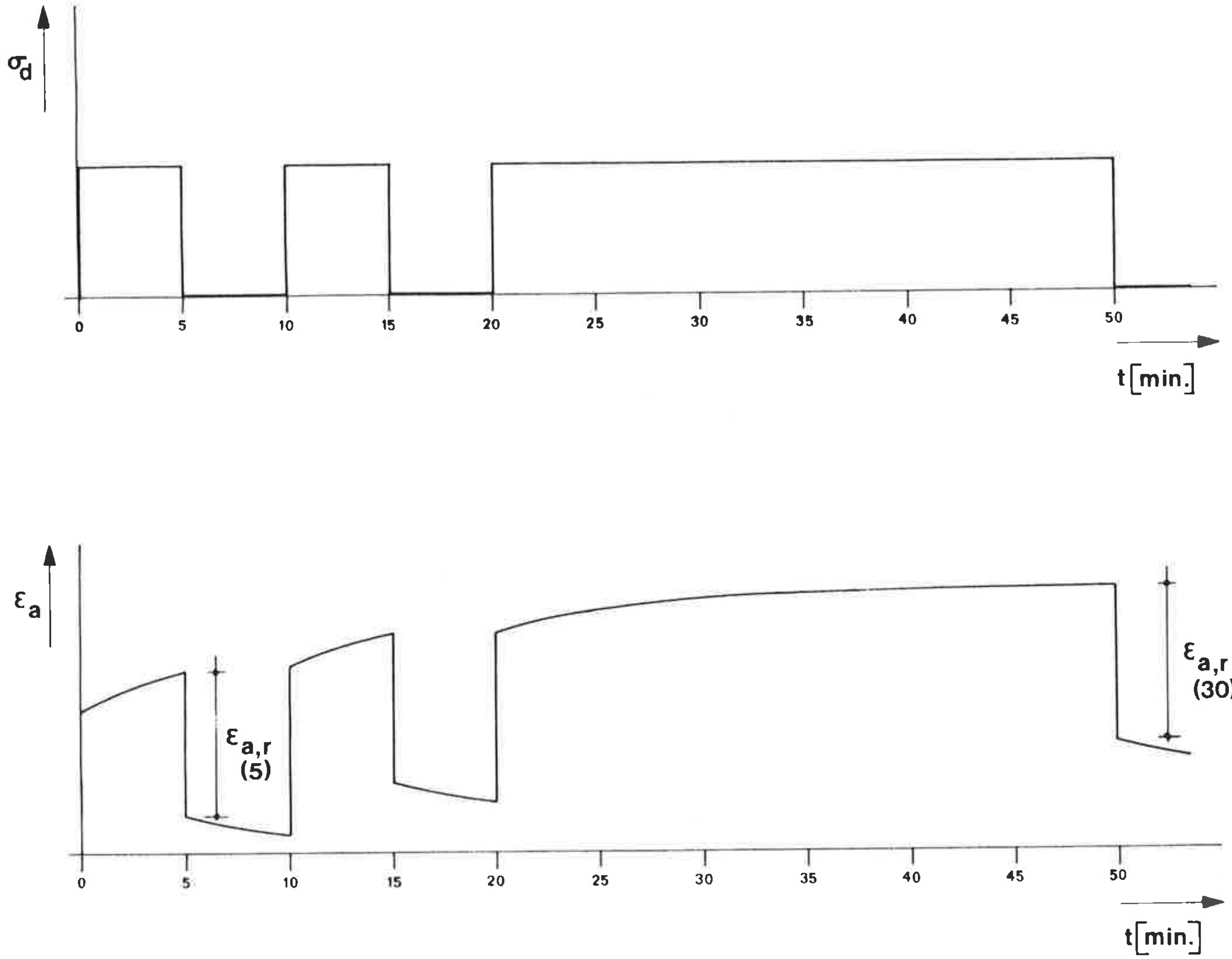

FIGURE 4 Deviator stress σ_d and axial strain E_a versus time for repeated static loading triaxial tests.

value of the multiple correlation coefficient squared R^2. The M_R-θ relationships for the other sands investigated are similar to the one depicted in Figure 5; to limit the length of this paper the individual graphs are not shown here. The resulting values of the material parameters K_1 and K_2 and the R^2 value for the six sands investigated are shown in Table 1.

REPEATED STATIC LOADING TEST RESULTS

The repeated static loading triaxial tests for determination of the resilient modulus were carried out at 10 different combinations of stresses. The axial resilient strain on unloading after the first 5-minute load-on period and the 30-minute load-on period (Figure 4) were determined, and the resilient modulus was then calculated according to

$$M_{R,s} = \frac{\sigma_d}{\varepsilon_{a,r}} \qquad (3)$$

where

$M_{R,s}$ = resilient modulus from repeated static loading test (MPa),
σ_d = deviator stress (MPa), and
$\varepsilon_{a,r}$ = axial resilient strain (–).

The individual data points shown in Figure 6 represent the results of the 10 repeated static loading tests for the Echteld sand, calculated from the axial resilient strain on unloading after the 30-minute load-on period. The straight line shown in Figure 6 is the regression line through the cyclic loading test results. To indicate the influence of the stress ratio σ_1/σ_3, different symbols have been used in Figure 6 for the three values of σ_1/σ_3 applied.

As can be seen from Figure 6, the data points from the repeated static loading tests plot closely to the regression line from the cyclic loading tests. The data points from the repeated static loading tests at stress ratio σ_1/σ_3 = 4

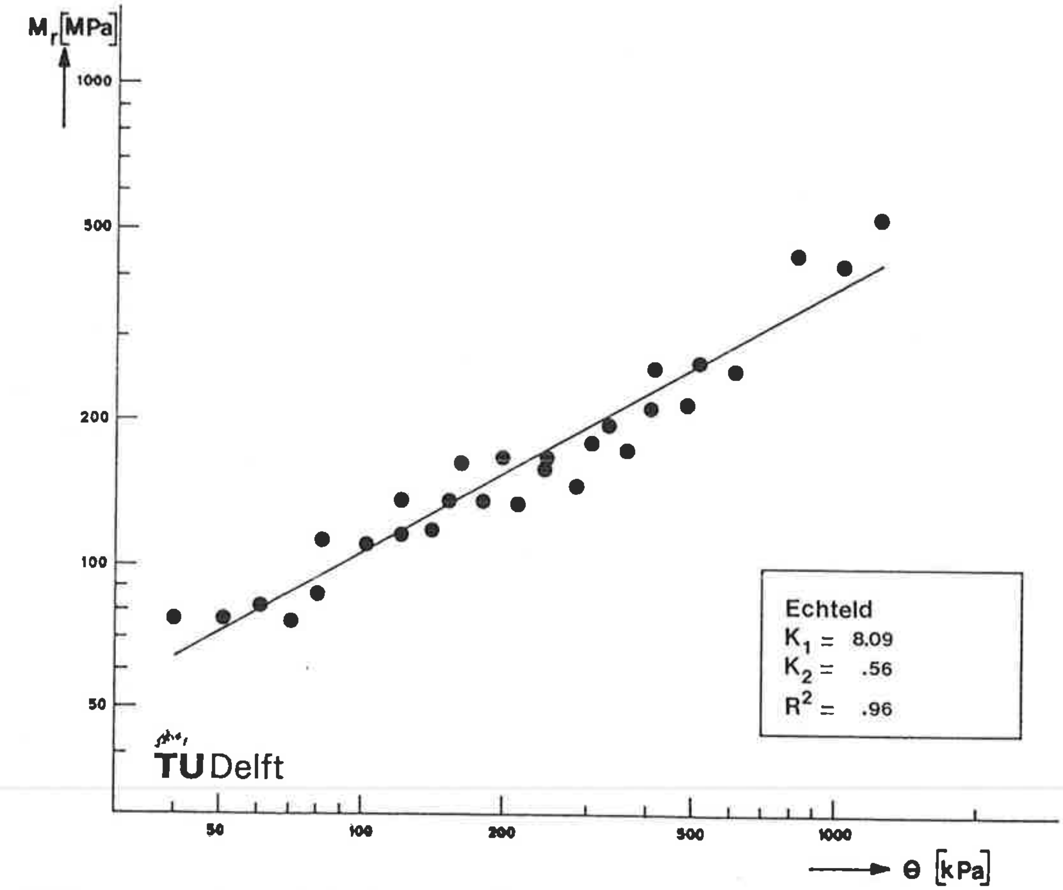

FIGURE 5 Results of cyclic loading tests: resilient modulus M_R versus sum of principal stresses θ, for Echteld sand.

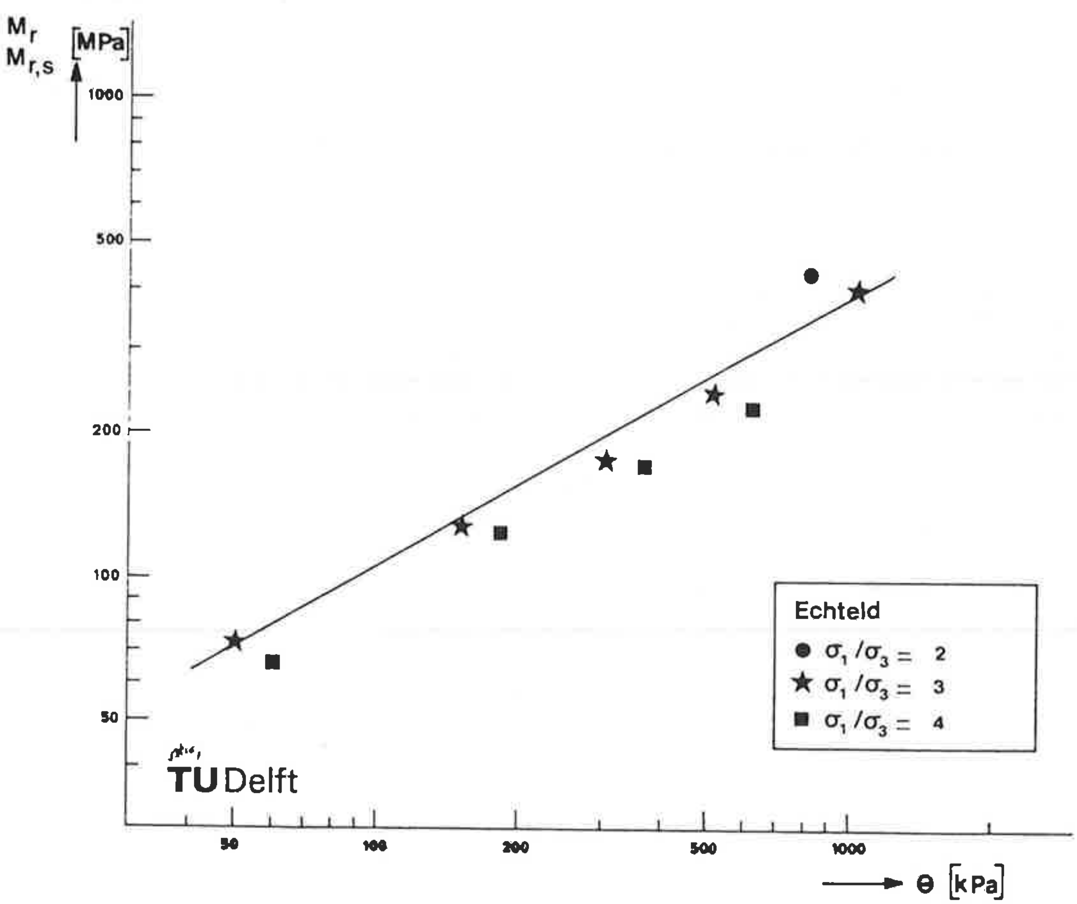

FIGURE 6 Comparison of cyclic loading (straight line) and repeated (static loading) test results.

plot somewhat below the regression line. For $\sigma_1/\sigma_3 = 3$, the data points almost plot on the regression line, and the single data point obtained for $\sigma_1/\sigma_3 = 2$ plots above the regression line. This influence of stress ratio is consistent with that found in the cyclic loading tests. Since the regression line from these tests represents all the stress ratios applied, it passes through the cyclic loading data points for the average stress ratio $\sigma_1/\sigma_3 = 3$. Therefore, the static loading data points for $\sigma_1/\sigma_3 = 3$ plot closest to the cyclic loading regression line.

For the other five sands investigated, results similar to those depicted in Figure 6 for the Echteld sand were found, with a similar influence of the stress ratio σ_1/σ_3. Space limitations prevent showing individual results for these sands here. In the next section of this paper, the data from the repeated static loading tests for all the sands investigated will be grouped together and compared to the results from the cyclic loading tests.

COMPARISON OF 5-MINUTE AND 30-MINUTE LOADING RESULTS

The repeated static loading procedure suggested by Kalcheff and Hicks (5) calls for a loading procedure as depicted in Figure 4, and calculation of the resilient modulus using the resilient deformation on unloading after the 30-minute load-on period. The $M_{R,s}$ results thus obtained are plotted in Figure 7 against the resilient moduli M_R from the cyclic loading tests. In Figure 7, the data from all the tests on the six sands have been used.

The straight line depicted in Figure 7 can be described by the following formula:

$$M_{R,s}\,(30) = -3.54 + 0.965\,M_R \quad (4)$$

$$R^2 = 0.988$$

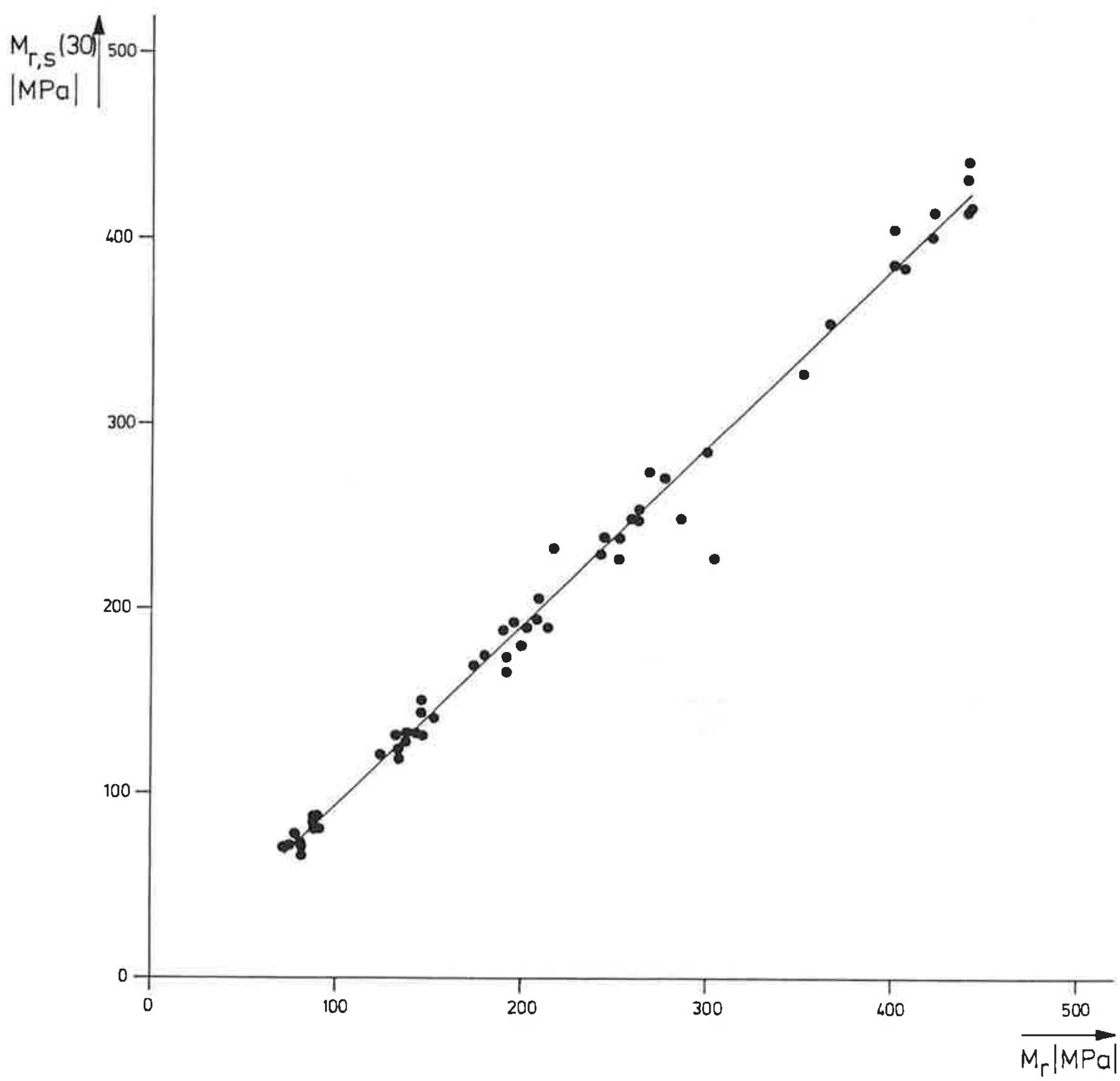

FIGURE 7 Comparison of resilient moduli from static 30-minute loading ($M_{R,s}$) and cyclic loading (M_R) test results.

where

$M_{R,s}(30)$ = resilient modulus from 30-minute static loading test,
M_R = resilient modulus from cyclic loading test, and
R^2 = multiple correlation coefficient squared.

As can be seen from Figure 7 and from the high R^2 value of equation 4, the correlation between the resilient moduli from the repeated static and the cyclic tests is very good. From equation 4, it can also be seen that the data plot almost on a 45-degree line of equality.

The loading procedure depicted in Figure 4 has one main disadvantage: for each determination of M_R, almost 1 hour is required. Since M_R has to be determined for several different combinations of stresses, this procedure is quite cumbersome. Therefore, the possibility of determining the resilient modulus using the resilient strain on unloading after the first 5-minute load-on period (Figure 4) was also investigated. The $M_{R,s}$ results calculated from those strain values are plotted in Figure 8 against the M_R values from the cyclic loading tests. Again, all the data from the six sands were used.

The straight line depicted in Figure 8 can be described by the following formula:

$$M_{R,s}(5) = -6.64 + 0.969\ M_R \qquad (5)$$
$$R^2 = 0.990$$

where

$M_{R,s}(5)$ = resilient modulus from 5 minute static loading test,
M_R = resilient modulus from cyclic loading test, and
R^2 = multiple correlation coefficient squared.

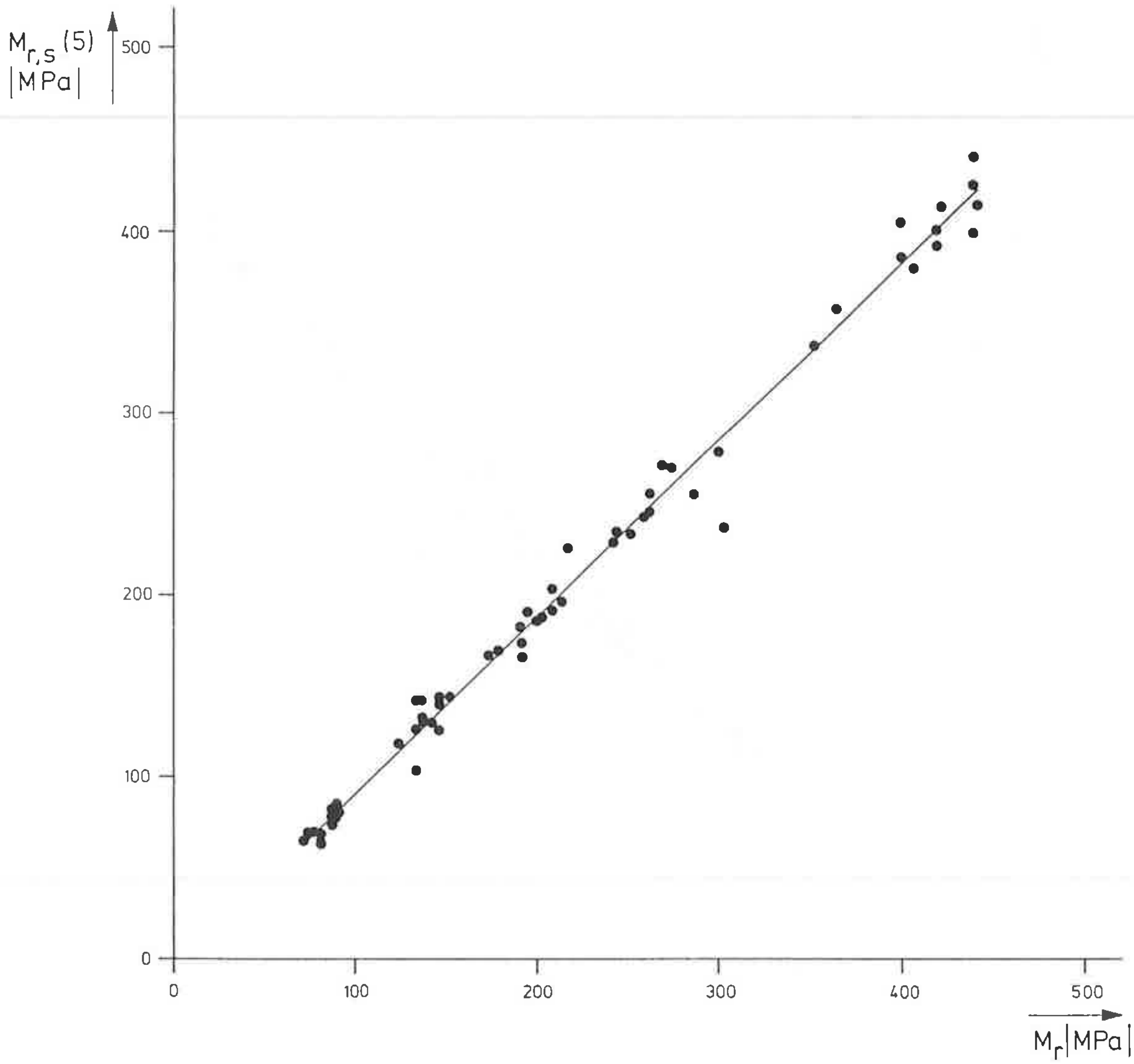

FIGURE 8 Comparison of resilient moduli from static 5-minute loading ($M_{R,s}$) and cyclic loading (M_R) test results.

Once more, a very good correlation between the repeated static loading and the cyclic loading test results is found, the data points again plotting almost on a line of equality.

Comparison of equations 4 and 5 shows that the 30-minute and the 5-minute loading procedure yield almost the same regression equations between $M_{R,s}$ and M_R, with almost the same R^2 value.

CONCLUSIONS

The research described in this paper has shown that, for a wide range of sands, the resilient modulus can be determined using relatively simple repeated static loading triaxial tests. Per stress combination to be investigated, one short load-on period of 5 minutes can be used to determine the resilient modulus. It is suggested, however, that 10 1-minute load-on periods at high confining stress and low stress ratio be executed before starting the actual measurements. Such a procedure assures proper seating between the loading caps and the triaxial specimen. Experience has shown that proper seating is achieved within a few load applications.

The possibility of determining the resilient modulus of coarse, graded crushed stone materials using the same repeated static loading procedure is currently being investigated by the authors.

ACKNOWLEDGMENT

These investigations were supported in part by the Netherlands Technology Foundation (STW).

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Publication of this paper sponsored by Committee on Soil and Rock Properties.