Shear Modulus of Silty Sand Reinforced by Carpet Waste Strips

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ABSTRACT

The most important parameters in evaluation of dynamic behavior of soil structures such as highways, retaining walls, and embankments are shear modulus and damping ratio. A fiber reinforced soil behaves as a composite material in which fibers of relatively high tensile strength are embedded in a matrix of soil. Shear stresses in the soil mobilize tensile resistance in the fibers, which in turn imparts greater strength to the soil. This study deals with assessment of fine sand reinforced with carpet and geotextile strips when subjected to dynamic loading by performing two sets of cyclic triaxial test- large scale and small scale. In these tests the influences of various parameters such as confining pressure, mixture ratio, and the ratio of strip length to its thickness which will herein be referred to as aspect ratio on the dynamic behavior of reinforced fine sand were studied. The results demonstrate that the effects of this kind of reinforcement on shear modulus in low confining pressures (less than 100kPa) are negligible and in high confining pressures are considerable.

Keywords:
Fiber reinforcement;
Shear modulus;
Cyclic triaxial;
Carpet waste

1. Introduction

Previous studies have proposed several improvement methods to increase tension and shear strength of soils. Soil reinforcement is one of the improvement methods in which tensile elements are set into the soil body to compensate the soil weakness in tension. In general reinforcing elements can be placed either in regular arrangements like latticed plates and textile ribbons, or in a randomly pattern like a mixture of textile strips and soil. Due to simplicity and applicability of mixing fibers with soil, several investigations in both laboratory and numerical fields in the 70's have been conducted. The focus of these studies was mainly on longitudinal elements utilization in regular arrangements.

The idea of randomly distributed fiber reinforcement was firstly presented in early 70’s and soon became the subject of several investigations. The results generally revealed that soil reinforcement using various types of fibers increases the strength and bearing capacity of soils. This finding is mainly reported in Lee et al [1], Gray and Ohashi [2], Gray and Rafeai [3], Maher and Gray [4], Wang et al [5], Michalowski and Cermak [6], and Ghiassian et al [7] among others.

It should be noted that these studies were focused on static loads. However, to obtain an estimation of the performance of this type of reinforcement, the problem should also consider the effect of dynamic loadings. Comparing to the studies performed in static loading, less investigations have been carried out for cyclic loading, especially on randomly distributed fiber reinforcement. Among such studies are Boominathan et al [8], Krishnaswamy and Isaac [9], and Vercueil et al [10] which mostly concentrate on evaluation of the dynamic behavior of soils reinforced with plane elements using cyclic triaxial test, torsion shear test, and resonant column test. Other studies such as Noorany and Uzdavines [11], Maher and Woods [12], Feng and Sutter [13], Li and Ding [14], and Boominathan and Hari [15] were focused on dynamic behavior of soils with randomly distributed fiber reinforcement. Despite the fact that Maher and Woods [12], and Feng and Sutter [13], mainly considered shear modulus and damping ratio variation of samples. With the same line of thought, in the present study the behavior of fine sand reinforced with randomly distributed carpet and geotextile strips subjected to cyclic loading *I* examined utilizing cyclic triaxial tests.

2. Material Properties

2.1. Soil Type

Two different types of sand have been used in this study. The soil type used in the small scale cyclic triaxial test is fine silty sand with low plasticity index having a specific gravity of 2.69 and particle average diameter (*D*50) equal to 0.26. According to the Unified Classification System, the soil is classified as *SM*. The optimum water content of this soil is 10% and its maximum dry density is 16.2*kN/m*^{3}. Figure (1) shows the particle size distribution curve for this soil. The second soil type used in the large scale cyclic triaxial test is the standard Toyoura sand whose material properties are summarized in Table (1).

2.2. Reinforcing Material

The reinforcing elements are short narrow strips of carpet and geotextile. The strips are constituted from polyethylene or polypropylene maximum tension strength and the initial modulus of elasticity are 800*kPa* and 730*kPa*, respectively [17]. The section of strips is square with 5*mm* in sides while the length of strips was selected 15.5*mm* and 45*mm*. The strips were mixed with sand by the ratio of 0.5 and 1 percent of the soil dry weight.

Table 1. The properties of the standard Toyoura sand [16].

Maximum Grain Diameter (mm)	D_{max} = 0.42
Mean Grain Diameter (mm)	D_{50} = 0.19
Fines Content (Less than 0.074mm)	F.C. = 0%
Specific Gravity	Gs = 2.65
Plasticity Index	P.I. = 16.8 (%)
Maximum Void Ratio	e_{max} = 0.98
Minimum Void Ratio	e_{min} = 0.60

3. The Standard Compaction Test

The standard compaction tests were conducted on plain samples as well as reinforced samples with a mixture ratio of 1 percent and aspect ratios of 1 and 3. The results are presented in Figures (2) and (3).

It can be observed that adding the strips leads to increasing the optimum water content and decreasing the dry density of samples. It might be due to the high water absorption and low density of strips comparing to soil materials. Since the values chosen for the side and mixture ratio of strips are the maximum values, the curves also specify the range of variation in the dry density of reinforced samples.

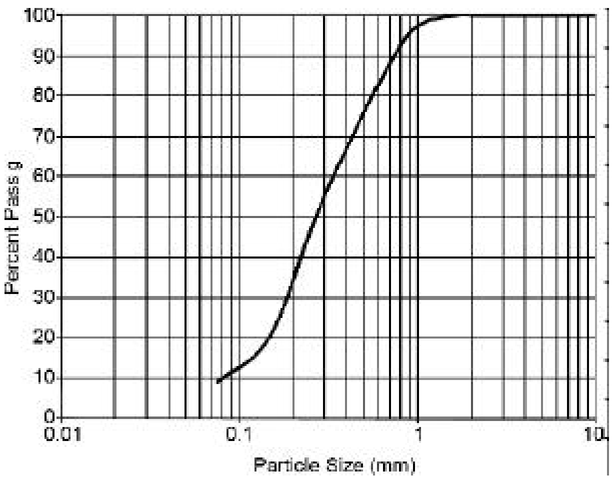


Figure 1. The particle size distribution curve for soil used in the small scale cyclic triaxial test.

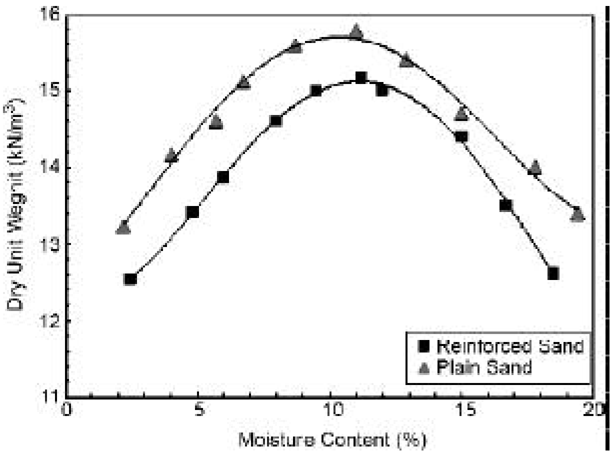


Figure 2. The compaction curves for plain samples and reinforced samples with 1% mixture ratio and 5mm long strips.

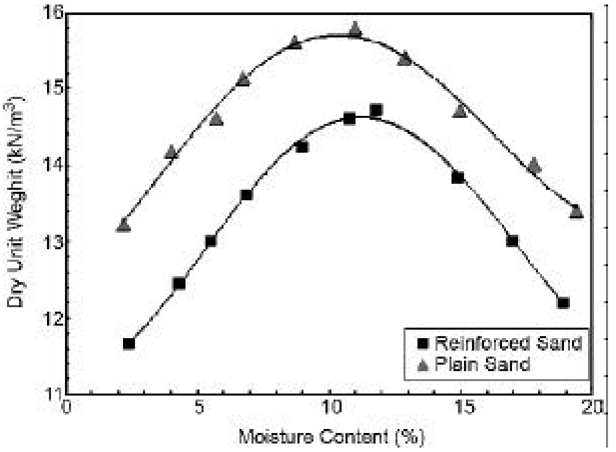


Figure 3. The compaction curves for plain samples and reinforced samples with 1% mixture ratio and 15mm long strips.

4. Small Scale Cyclic Triaxial Test

To evaluate the dynamic behavior of fine sand reinforced with carpet strips, several stress-controlled cyclic triaxial tests were performed. These tests were carried out to study the effects of mixture ratio (W_f) and side ratio (*AR*) on the stress-cyclic strain curve, cyclic strength, pore pressure variation, shear modulus, and damping ratio in different confining stresses under undrained conditions. The mixture ratio of samples was 0, 0.5, and 1 percent with the side ratio of 1 and 3. The samples were firstly saturated and consolidated in the confining stresses equal to 20, 100, 400 and 700*kPa* and then tested in undrain condition. These tests were performed in the Soil Mechanics Laboratory of the International Institute of Earthquake Engineering and Seismology, (*IIEES*) of Iran. Tests were examined according to *ASTM D* 3999-91 applying a constant cyclic loading. The device is shown in Figure (4).

The pneumatic loading system of the device is provided by a 14 bar air compressor. The vertical load and deformation as well as pore pressure and volume changes are measured by several electronic transducers in terms of voltage variation. These data are transmitted into a voltage amplifier. A data acquisition system interprets and records the information received from the voltage amplifier. The general specifications of the device are summarized in Table (2).

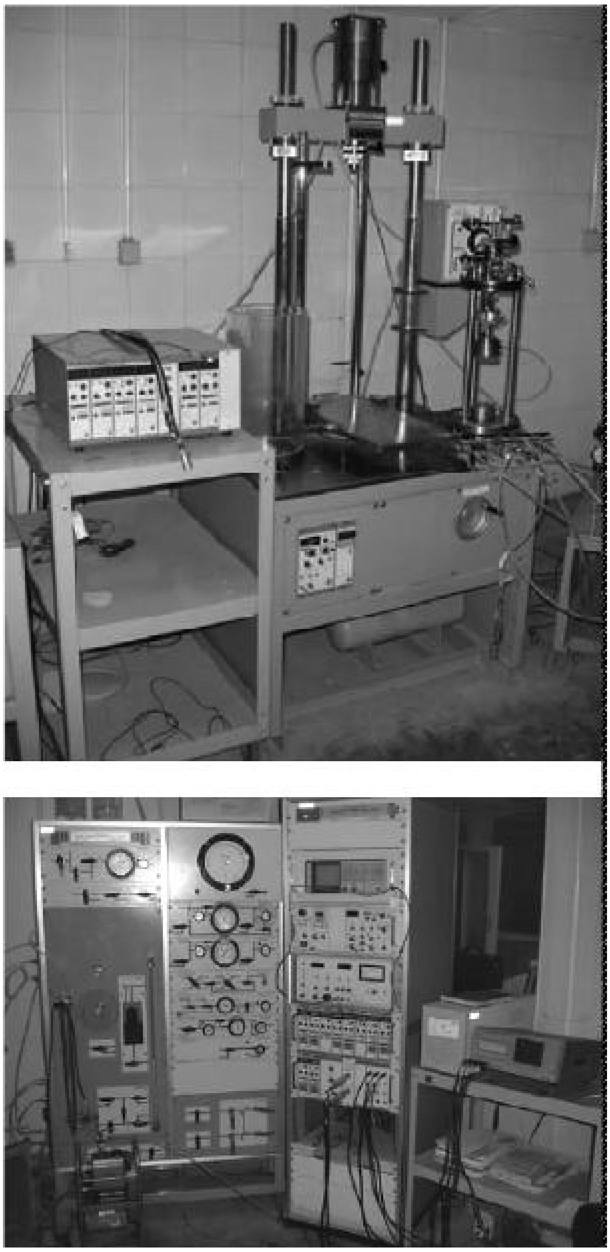


Figure 4. A general overview of the cyclic triaxial test.

Table 2. The general specification of the cyclic triaxial test.

The capacity of Lifting Jack	5tonf
Maximum Vertical Force	±200Kgf
Maximum Confining Pressure	1000kPa
Loading Frequency	0.001 ~ 100Hz
Maximum Sample Diameter	70mm

4.1. Sample Preparation and Testing Procedure

Since the carpet strips prevent the bottom layers of the sample to be extra compacted, applying the reduced compaction method is not appropriate; so, the wet tamping method is applied in this study. It can be deduced from the compaction curve presented in Figure (3) that for samples reinforced by 15*mm* long strips, the maximum dry density is 14.53kN/m^3. This value which is an average compaction and refers to 50 percent of the standard compaction is chosen for remolding samples. Samples with diameter of 70*mm* and height of 140*mm* are compacted in 5 layers at the moisture content of 10% to reach the dry density of 14.53kN/m^3. Figure (5) shows the procedure of samples preparation.

Figure 5. The procedure of preparing the samples.

The samples were saturated and consolidated in confining stresses equal to 25, 100, 400, and 700*kPa* before applying the dynamic load. The dynamic load was a sinusoidal load with the frequency of 0.5*Hz* which was applied in several steps, see Figure (6). During each loading step the draining valves located at the top and bottom of the cell are closed. These valves opened at the end of loading in each step to allow the induced water pressure to be dissipated. This procedure has been performed in each loading step (*ASTM D* 3999). The water content of each sample was measured after the test. The histories of pore pressure at the top and bottom point of the sample, axial displacement, shear strain, and deviatoric stress as well as the stress path were then obtained. The test results performed on a sample reinforced by carpet strips with side ratio of 1 and mixture ratio of 0.5 percent at the confining stress of 100*kPa* after the 10^{th} loading step are presented in Figures (6) to (8).

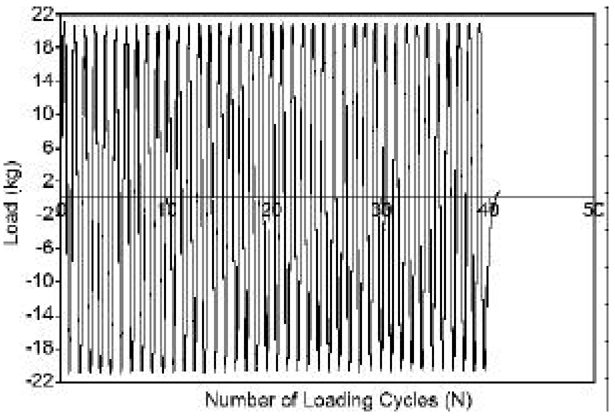


Figure 6. The loading history (W_f = 0.5%, AR = 1, $\sigma 3$ = 100 kPa).

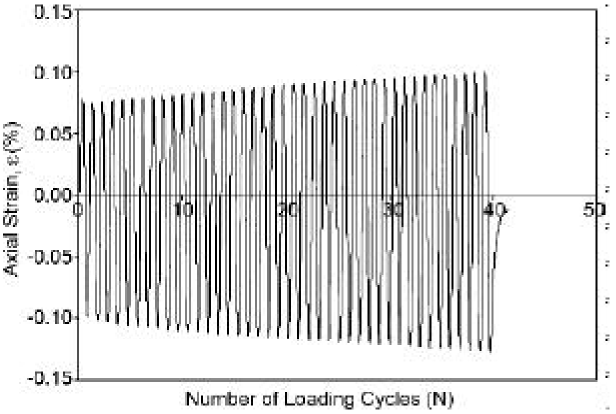


Figure 7. The history of axial strain (W_f = 0.5%, AR = 1, $\sigma 3$ = 100 kPa).

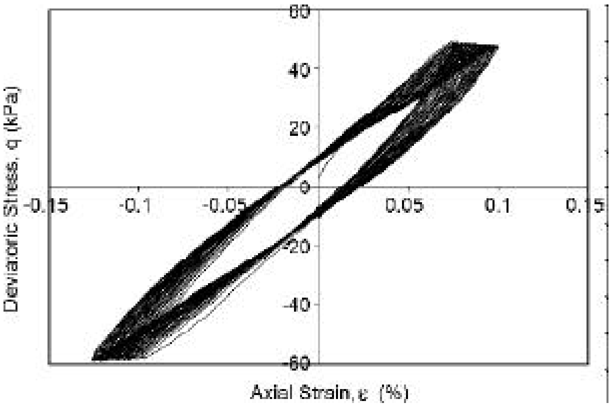
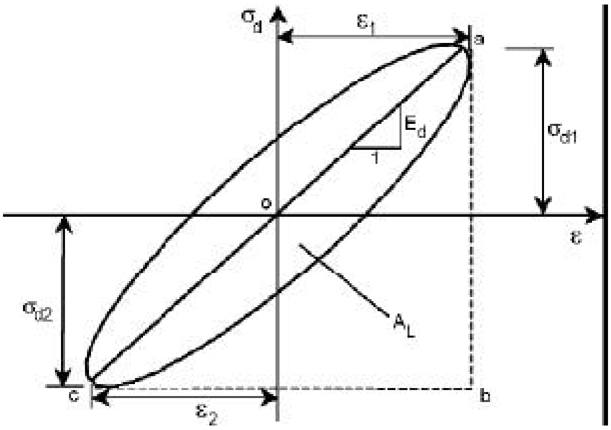


Figure 8. The hysteresis loops (W_f=0.5%, AR = 1, $\sigma 3$=100kPa).

4.2. Determination of Shear Modulus

At the end of each test, the stress-shear strain (or axial strain) hysteresis loops are developed to determine the shear or axial modulus as depicted in Figure (9) [18]. It should be mentioned that these parameters can be also determined in each loading cycle. However, Kukusho [19] and Ishihara [20] have recommended to use the 10^{th} loading cycle because after around 10 cycles the hysteresis loops reach the steady state. According to this recommendation, the 10^{th} loading cycle has been adopted as the basis of such calculations. The *MATLAB* software has been utilized to facilitate the calculations.



$$E_d = (\sigma_{d1} + \sigma_{d2}) \big/ (\varepsilon_1 + \varepsilon_2)$$

Figure 9. The stress-strain hysteresis loop [18].

5. The Large Scale Cyclic Triaxial Tests

In addition to the aforementioned small scale triaxial tests, some large scale tests were examined on Toyoura sand reinforced by geotextile strips. These tests were performed on dry samples with mixture ratios of 0, 0.5, and 1 percents and the side ratios of 3 and 9 at the confining pressure of 50*kPa* using the large triaxial test device at the Soil Mechanics Laboratory of the University of Tokyo, see Figure (10). Since this device could not apply the confining stress by liquid pressure, the desired confining stress was provided in vacuum condition.

The loading system applied in this device is of the gear-clutch type which is controlled by an *AC*-Servo motor. This loading system is a strain-control type capable to induce strain rate up to 0.1% per minute.

The main problem in using this loading system was that the data logger was not fast enough to perform well in high loading rates. Therefore, the amplitude of the induced load became greater than the desired value. To avoid this inaccuracy, the loading rates were kept below a value which was determined in some preliminary tests. Figure (11) shows the overshooting error.

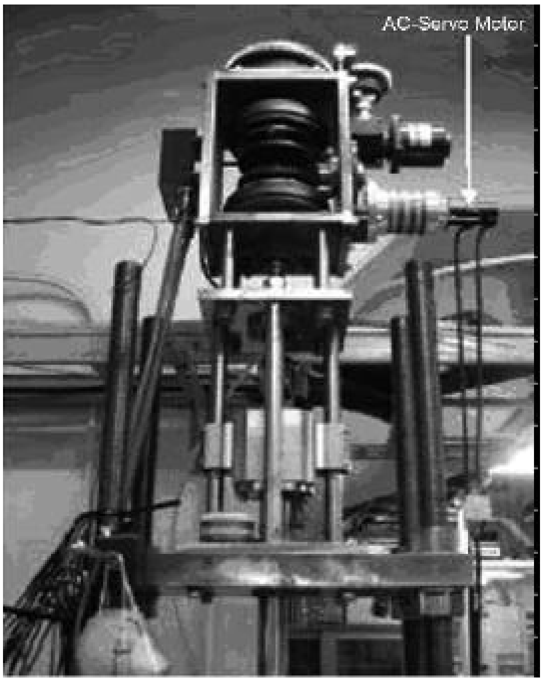
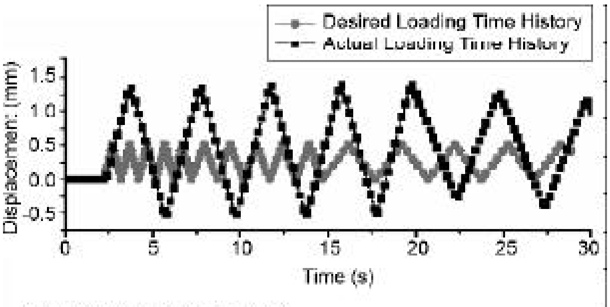


Figure 10. The gear-clutch type loading system at the laboratory of soil mechanics in the University of Tokyo. [21-22].



Desired Loading Time History:
- Loading Amplitude = 0.25mm
- Loading Frequency = 60mm/min (1Hz), 40mm/min (0.67Hz), 20mm/min (0.33Hz)

Erros:
1- Delay in the Dutch-Break Switch System
2- At 1Hz Cyclic Loading, the Reliable Control Feedback Frequency = 40Hz. Present System has Only 4Hz Reliable Control Feedback Frequency

Figure 11. The gear-clutch type loading system errors.

5.1. Sample Preparation and Testing Procedure

Since the strips cannot be uniformly distributed in sand using common mixing methods such as dry falling or sedimentation in water, the only available method is dry or wet compaction. In the large scale tests, the samples had to be dry; so, the dry compaction method has been used to remold the samples.

The internal diameter of the mold is 300*mm* while its height is 600*mm*. The exact amount of sand and stripe required to prepare each sample was determined before making the samples. The samples were then remolded in 6 layers each 100*mm* thick. To make a logical comparison between the behavior of reinforced and plain samples, the density of samples should be equal. However, since the volume of strips subjected to significant changes during compaction, the density of the sand fraction can not be precisely controlled. Therefore, the weight of sand amount was kept constant for all samples and then the weight of strips was computed based on the desired mixture ratio. As mentioned before, the geotextile strips were manually mixed in sand at a dry condition to achieve a homogeneous material. Figure (12) illustrates the different stages of preparing a sample.

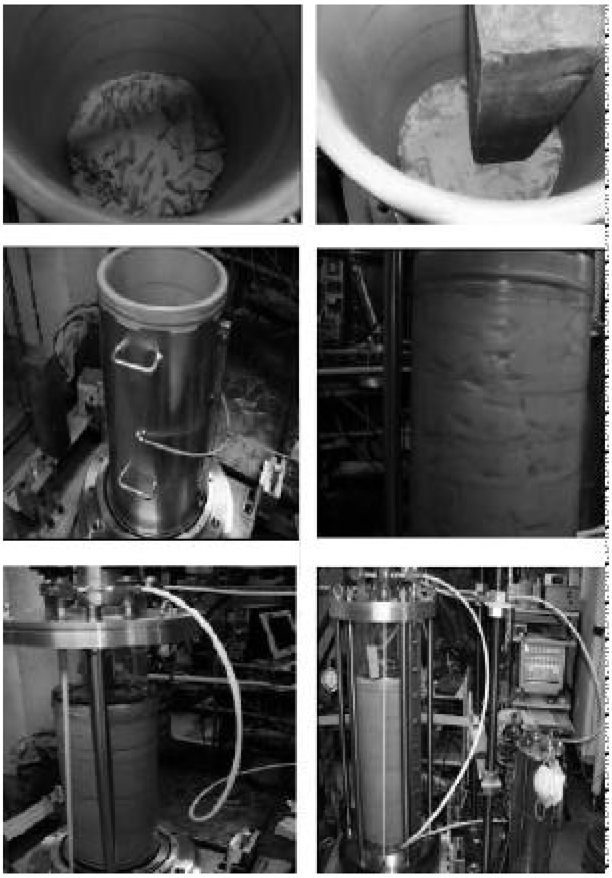


Figure 12. Samples preparation for large scale tests.

5.2. *Determination of Axial Modulus*

As stated before the cyclic load is applied in 10 cycles but the first and the last two cycles were omitted and the remaining 7 cycles were considered as the basis of determination of damping and shear modulus. Figure (13) shows a stress-axial strain curve obtained from a large scale triaxial test. Since the volume changes can not be exactly measured, the calculations were mainly based on axial strain.

6. Test Results

6.1. *The Results of Small Cyclic Triaxial Test*

6.1.1. The 25kPa Confining Pressure

Figures (14) and (15) present the variation of shear modulus (G_s) with respect to the shear strain for different mixture ratios (W_f) and side ratios (AR).

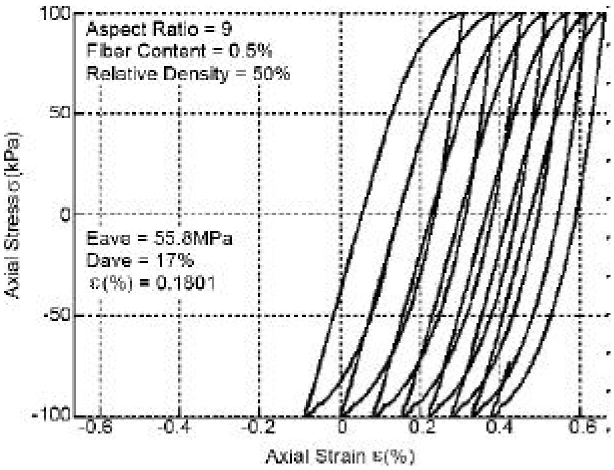


Figure 13. The stress-axial strain loops for a large scale triaxial curve.

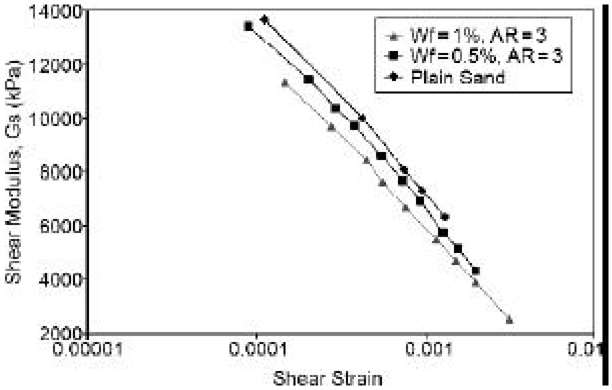


Figure 14. The effect of mixture ratio (W_f) on variation of shear modulus (confining stress = 25 kPa).

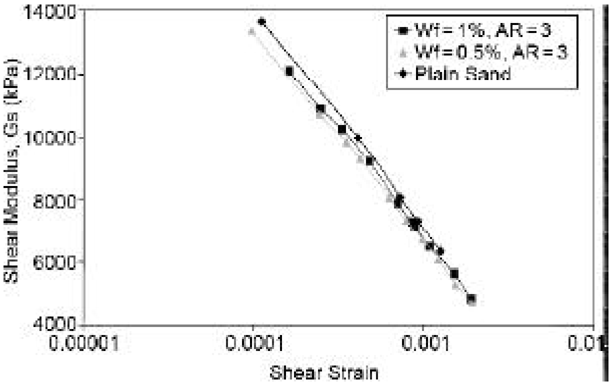


Figure 15. The effect of side ratio (AR) on variation of shear modulus (confining stress = 25kPa).

6.1.2. The 100kPa Confining Pressure

Similar to the results for 25*kPa* confining pressure, it can be observed that adding strips will lead to decrease the shear modulus of samples. Figures (16) and (17) confirm this statement.

The test results show that as the mixture ratio increases, the shear modulus decreases illustrated a good agreement with what previously found out from static triaxial tests. The static tests show that the elastic modulus of reinforced samples is less than that of plain samples. The elastic modulus of reinforced samples decreases while the mixture ratio or side ratio increase. In other words, increasing the mixture ratio or side ratio results in increasing the ductility of the reinforced mass and therefore higher strain rate will occur at the failure point [17]. The results also reveal that by increasing the side ratio, and consequently increasing the volume of strips in a sample, the induced energy will be more dissipated and the failure strain will increase, and therefore the shear modulus will reduce.

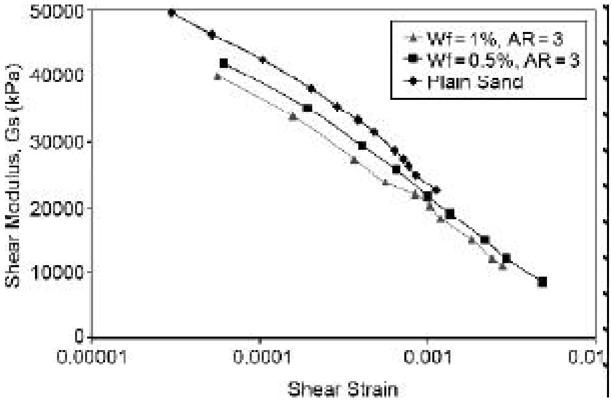


Figure 16. The effect of mixture ratio (W_f) on the variation of shear modulus(confining stress =100kPa).

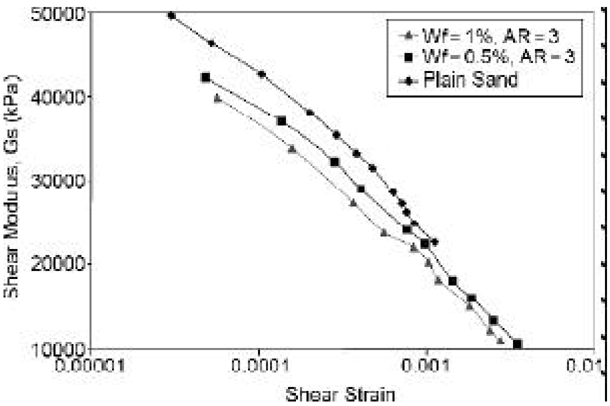


Figure 17. The effect of aspect ratio (AR) on the variation of shear modulus(confining stress=100kPa).

6.1.3. The 400kPa and 700kPa Confining Pressures

Contrary to the results obtained from the tests performed in low level confining stresses (up to 100*kPa*), it became clear that the shear modulus of reinforced samples is higher than that of plain samples in high level confining stresses. Figures (18) and (19) present the variation of shear modulus versus shear strain for different mixture ratios and aspect ratios.

This fact can be explained by assuming larger shear strength between soil and strips in higher stress levels. Since developing the shear strength between soil and strips depends on the confining stress value, then the shear strength can not be fully developed. Indeed, the axial strength of samples reduces due to the replacement of soil with strips. In high confining stresses, however, the shear strength between the soil particles and strips are completely developed so the stiffness of samples will increase. This finding is consistent with previous studies [12].

It can be seen that by increasing the mixture ratio from 0.5 to 1 percent, the shear modulus decreases.

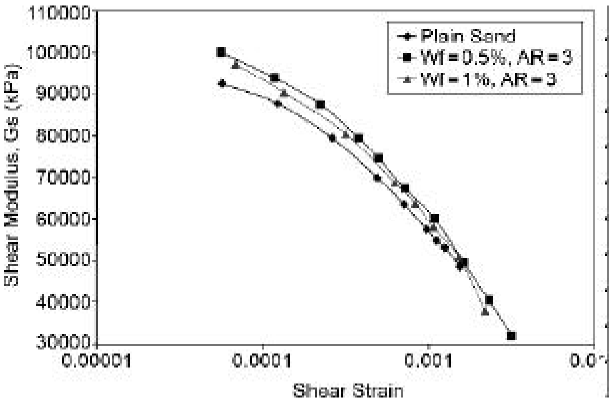


Figure 18. The effect of mixture ratio (W_f) on the variation of shear modulus(confining stress=400kPa).

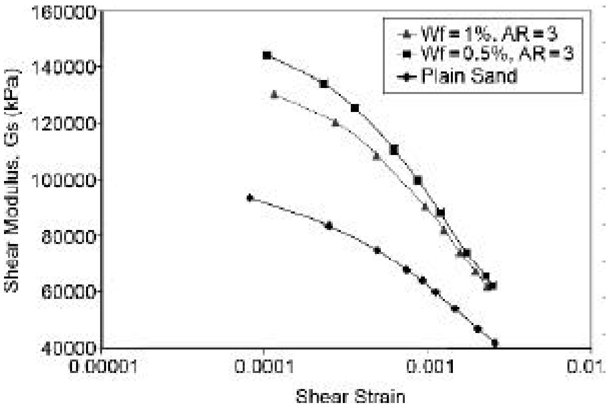


Figure 19. The effect of mixture ratio (W_f) on the variation of shear modulus(confining stress=700kPa).

The reason is clear as by assuming an optimum value for mixture ratio, the strips will constitute a large fraction of the sample and consequently an effective contact between the soil body and therefore the reinforcing element can not be well developed.

6.2. The Results of Large Scale Cyclic Triaxial Test

Figures (20) and (21) demonstrate the effects of mixture ratio and side ratio on the variation of axial stiffness in both plain and reinforced samples. It can be concluded that by increasing the mixture ratio, the axial modulus decreases. This finding is similar to the results of the small scale cyclic triaxial tests. Since the confining stress level in the large scale test is low, the performance of the reinforcing elements is inadequate and the replacement of stiff sand particles with soft strips leads to reducing the average stiffness of the sample.

The test results also show that by increasing the side ratio or in other words by increasing the length of strips in a constant mixture ratio, the axial stiffness of the sample decreases significantly. The reason can be found in decreasing the effective contacting area between soil particles and strips due to increasing the stripe length. It means that in a constant mixture ratio and a low confining stress, if shorter strips are used, the reducing effects of reinforcing on axial stiffness will decrease and a better soil-stripe contact will be developed. On the other hand, by using long strips, some soft deformable points will be developed in the sample which their effects lead to decreasing the general stiffness of the sample.

7. Conclusions

Both small and large scale triaxial tests performed on fine sand reinforced by strips of carpet and geotextile revealed negligible effect of reinforcement in low confining stresses (less than 100*kPa*) and high influence of reinforcement in high confining stresses. The obtained results are summarized below:

- The presence of strips leads to increasing the deformability of reinforced samples comparing to plain samples. Consequently, the strain induced in the reinforced samples at the failure point will be higher than that of plain samples.
- The axial and shear modulus of the reinforced samples will decrease in low confining stresses

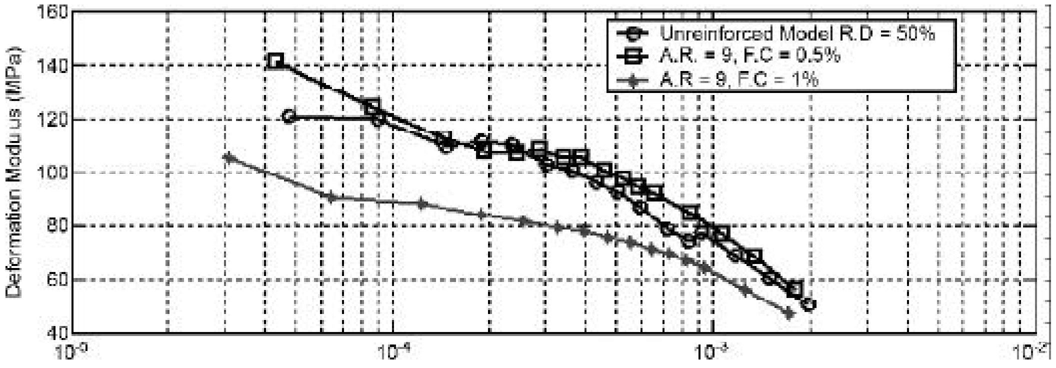


Figure 20. The effect of mixture ratio (W_f) on the variation of axial modulus (confining stress = 50kPa).

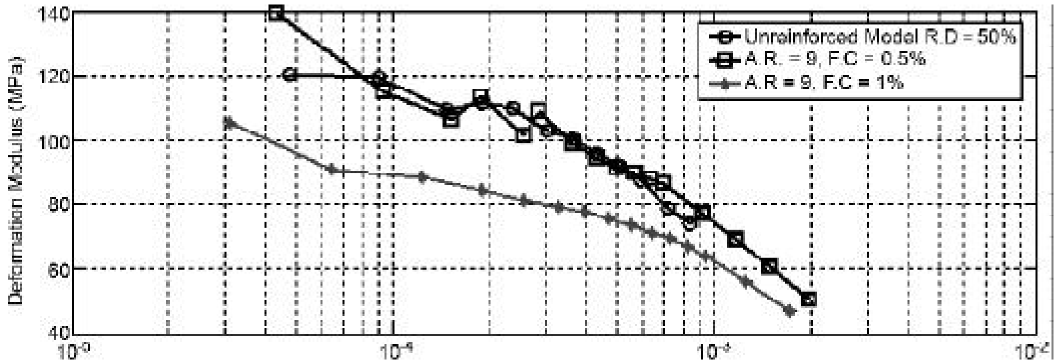


Figure 21. The effect of side ratio (AR) on the variation of shear modulus (confining stress = 50kPa).

(less than 100*kPa*) and increase in high confining stresses comparing to plain samples. It is obvious since the shear strength between the soil and strips will be increased by enhancing the stress level. On the other hand the shear strength of strips does not fully developed in low stress levels.

- In a constant mixture ratio, by increasing the aspect ratio from 1 to 3, shear modulus decreases.
- By increasing the mixture ratio from 0.5 to 1 percent the shear modulus of samples decreases for a constant aspect ratio at high stress level; therefore, an optimum value for mixture ratio can be determined. When the mixture ratio goes further than the optimum value, the contact of soil and strips decreases and consequently the performance of reinforcement reduces.

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