SIMPLE SHEAR AND BENDER ELEMENT TESTING OF GEOFOAM

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ABSTRACT

The engineering properties of geofoam (expanded polystyrene, EPS) were investigated, and the results of a series of simple shear and bender element tests on geofoam are presented. The measured simple shear response was compared to the response of geofoam under compression loading reported in the literature. The shear modulus and its variation with strain level were assessed using specimens subjected to a vertical stress of 28 kPa. Such studies provide means of assessing the response of geofoam under seismic loading. Modulus reduction curves for geofoam at different densities are similar, even though the actual shear modulus increases with density and is loading rate dependent. Initial results of a complementary study to assess the elastic modulus at low strain levels using bender element tests are also presented.

KEY WORDS

Bender elements, compression, density, EPS, geofoam, modulus, simple shear, p-wave, velocity

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INTRODUCTION

Low density expanded polystyrene (EPS) material has been used in geotechnical engineering applications for several years. This synthetic material, commonly termed geofoam, is primarily used as a low weight soil replacement refill in order to decrease the overburden pressure and thus to limit settlements, and for insulation purposes. The density of geofoam can be varied based on the production process, and those that have a density of about 20 ~ 30 kg/m^3 are commonly used in geotechnical engineering applications. To date investigations of geofoam behaviour have mainly focused on monotonic compression loading, interface strength and creep response for design under steady load conditions. The use of geofoam is becoming increasingly common. Further understanding of the mechanical behaviour of geofoam and its interaction performance is useful for design. Under field loading conditions geofoam fills may be subjected to seismic and other periodic loads. Fundamental studies are required to understand and model the response under such loading. This paper presents the initial results of a study performed to assess the deformation characteristics of geofoam under controlled conditions in the laboratory.

MECHANICAL BEHAVIOUR OF GEOFOAM

An understanding of the mechanical behaviour of geofoam is essential for proper design in geotechnical applications. Even though geofoams have been in use for about 30 years, studies of its mechanical behaviour under diverse loading conditions have so far been limited. Earlier interest was on the compressive strength of geofoam (Sorlie et al., 1979, van Dorp, 1988, Eriksson and Trank, 1991, Duskov, 1997, Negussey, 1997, BASF, 1998, and Elragi 2000), generally based on testing small samples at relatively faster loading rates. Negussey and Jahanandish (1993) studied the one dimensional compression behaviour of geofoam in contrast with the consolidation characteristics of soils. These studies indicate the behaviour of geofoam under compressive stresses is density, stress level, and loading rate dependent, and the stress - strain response may be approximated as elastic at low strain levels. Creep deformation in small samples was found to be relatively small up to stresses of about 30 to 40 percent of the compressive strength at strain levels of 5 to 10 percent. This background has been the basis for most current methods of design.

In the field, geofoam can be subjected to compressive as well as shear loads. An understanding of the behaviour under shear loading is important in the context of seismic loading. The first step in assessing seismic response is to comprehend the nature of shear stress-strain behaviour, factors influencing shear modulus, and the degradation of modulus with strain level. The shear modulus of soils depends on density among other factors, and extensive data is available in the literature covering modulus degradation with strain level for several soil types. While there is some published information covering repeated loading and creep effects (Hillman, 1996), investigations that address dynamic geotechnical behavior of geofoam are severely limited.

EQUIPMENT & TEST PROCEDURE

The stress stain behaviour of geofoam was assessed under simple shear loading conditions using an NGI type simple shear device. The loading pedestals in the device were modified to properly accommodate the geofoam specimen. Figure 1 shows a schematic diagram of the simple shear apparatus used. A single acting air piston applies the vertical load to the sample. The horizontal shear stress can be applied either by the double acting pneumatic piston for stress controlled, or by the variable speed motor drive for strain controlled loading. The loading mechanism permits switching to displacement controlled from stress controlled loading during a test. Normal and shear loads were measured by the vertical and horizontal load cells. Vertical deformation was monitored by a displacement transducer, and shear distortion was measured by horizontally positioned displacement transducers (LVDT). Two LVDTs were used in the horizontal direction in order to increase the available displacement range and yet have high measurement resolution at low strain levels.

Cyclic loading was applied by changing the pressure in one of the two chambers of the double acting piston using an electro-pneumatic transducer. The electro pneumatic transducer was controlled by a computer. An air volume booster was connected to the chambers of the double acting piston in order to maintain constant amplitude of cyclic shear load as large deformations occurred. The high resolution, high-speed data acquisition system enabled consistent determination of stresses and strains. The normal and shear stresses have a measurement resolution of about 0.3 kPa, and the vertical strain has a resolution of about 0.01%. The resolution of the shear strain evaluation was about 0.01% for shear strains up to about 10%, and 0.05% for shear strains in excess of 10%. The electro-pneumatic transducer has a resolution of about 0.3 kPa. This simple shear device has been used extensively to characterize the constant volume behaviour of sands. Further details of the equipment can be found in Vaid and Sivathayalan (1996).

One of the major challenges faced during the early stages of the test program was to ensure that the shear load was properly transmitted to the specimen at the pedestal-specimen interface (without slippage). When testing soils, shear stresses are transmitted by using approximately 1mm high ribs or pins in the pedestals. Such a setup was not suitable for testing geofoam, and an alternative way to glue the geofoam to the pedestal was devised. Different adhesives were evaluated and fast-curing epoxy was found to be the most suitable.

Tests were performed on geofoam samples of average 20 and 30 kg/m^3 densities. Cylindrical geofoam specimens of 70 mm diameter and about 20 mm high were glued to the top and bottom pedestals. A vertical stress of about 5 kPa was applied just after set-up, and sufficient time was allowed for the epoxy to cure and form a strong bond. Subsequently, a vertical stress of 28 kPa (to simulate a pavement dead load) was applied, and the vertical compression of the geofoam was monitored during the loading. The prescribed horizontal stress cycles were applied under this essentially constant vertical stress level. Both stress and strain controlled loading were used to apply the horizontal shear stresses.

The elastic modulus of geofoam was determined from "bender element" test results. A bender element is a special piezoceramic transducer capable of converting electrical pulses into mechanical vibration and vice-versa. They are being increasingly used in geotechnical engineering to measure the elastic properties of soils since Dyvik and Madshus (1985) demonstrated excellent agreement in shear modulus determined using resonant column and bender element tests. Strains generated by bender elements in testing of soils are in the range of 10^{-3} to 10^{-5} % (Brignoli et al. 1996). Therefore this test may be suitable to evaluate the elastic properties of geofoam. Details of the use of bender elements in soil dynamics is given by Gohl and Finn (1991).

The top and bottom pedestals of a conventional triaxial cell were modified to include bender elements. A vibrating bender element transmitter (approximately 12 mm x 10 mm in size) was placed at the bottom pedestal and the receiving element at the top pedestal as schematically illustrated in Figure 2. Cylindrical geofoam specimens of 20 kg/m^3 density 60 mm diameter and about 120 mm height were tested under a seating load of about 5 kPa. The bender elements were placed parallel to the base of the cell to generate compression waves during excitation. The time required for the elastic waves to travel from the bottom to the top of the geofoam specimen was measured using an oscilloscope that traces the voltage - time histories of the transmitted and received signals. A function generator capable of applying various waveforms over a range of frequencies was used to excite the transmitting element. The response of the received element was the strongest for frequencies ranging from about 400 to 1500 Hz for sinusoidal pulses at maximum amplitude of ±10 V. The time of travel was taken as the time difference between the peaks in the transmitted and the received signals.

TEST RESULTS

AXIAL COMPRESSION OF GEOFOAM

The axial compressibility of the geofoam was measured by using the simple shear device. No adhesives were used when testing axial compressibility since the loading was only axial and the specimen was confined between the end platens. A vertical stress of up to 100 kPa was applied in increments over a period of 12 hours and the vertical deformation was monitored. This is shown by the solid line in Figure 3. Also shown in Figure 3 are the data obtained for several samples during the application of the vertical load in simple shear tests. The specimens tested in shear were bonded to the end platens using epoxy. The compressibility of the specimen in shear tests can be noted to be essentially similar to that in the compression tests where no adhesives were used. This indicates that use of epoxy did not alter the measured load-displacement characteristics. Two other adhesives were tested instead of the epoxy, vertical strains (as high as 30%) developed for the same stress level of 28 kPa. Even though good bonding developed between the aluminum pedestal and the geofoam, some chemical interaction and softening of the geofoam portions at the edge occurred.

SHEAR STRESS-STRAIN BEHAVIOUR

The shear stress-shear strain response of geofoam under monotonic simple shear loading is shown in Figure 4. The specimen was sheared at a rate of about 0.7% per min. Geofoam strengths based on unconfined compression tests are commonly reported for strain levels of 5% and 10%. The shear strength at 5% shear strain is about 33 kPa, and the strength at 10% strain is about 36kPa. The variation between strengths at 5% and 10% strain may be noted to be about 10%. This is similar to the behaviour commonly observed for geofoam under uni-axial compression. Elragi (2000) reports that geofoam of the same density subjected to uni-axial compression at 0.1% and 100% percent strain rates developed shear strengths of about 140 and 200 kPa at 5% strain and about 160 and 220 kPa at 10 % strain. However, corresponding shear strengths that may be inferred from the uni-axial tests are much higher than values derived from simple shear.

Figure 5 shows the stress-strain response and the variation of stress and strain with time for a geofoam specimen subjected to three stages of cyclic loading to strain levels of ±0.1%, ±0.5% and ±1.0% shear strain in simple shear. Three cycles of loading were applied within each stage. The shear stress developed to reach a given strain level (within the three cycles of loading at a given stage) remains essentially constant at low strain levels. The test was performed using displacement controlled loading, and the system compliance (mostly from the gear slack) was the cause of the spikes and flat peaks in both the strain and stress traces. However, no such compliance problems developed, when the load-controlled mechanism was used to apply the cyclic stresses as shown in Figure 6. Again, three stages of loading, but this time with ten cycles per stage, at shear stress levels of ±5, ±10 and ±15 kPa, were applied. One stress cycle was applied per minute, and this resulted in variable strain-loading rate. The loading rate during the first stage corresponded to about 0.8% shear strain per min, and the third about 2.5 % per min. The strains developed within each stage may be noted to be essentially constant. The secant shear modulus under a cyclic stress level of ±10 kPa remains at an essentially constant value of about 2.2 MPa. A constant shear modulus within a stage of loading indicates that the applied cyclic loading does not cause degradation in the modulus at the stress level. However, when larger amplitudes of cyclic shear stresses were applied, as illustrated in figure 7, the specimen exhibited some softening within a "stage" due to cyclic loading. The initial secant shear modulus under the cyclic stress level of ±50 kPa was about 1.3 MPa, but decreased to about 1 MPa during the next 10 loading cycles at the same stress level.

Figure 8 shows the variation of shear modulus in simple shear with strain level. The initial shear moduli determined under simple shear loading are about 1.7 and 2.3 MPa for geofoam of 20 and 30 kg/m^3, respectively, when tested under a constant strain loading rate of about 0.7 % per min. A significant degradation in shear modulus may be noted at initial low strain levels. The modulus is higher for denser geofoam, but the rate of modulus reduction appears essentially independent of the density. Dependence of Young's modulus on density and size of geofoam has been established from uni-axial compression tests (Elragi et al, 2000). Modulus degradation with strain has been well established in soils, and the characteristics of the modulus degradation curve in geofoam appear to be similar to that of soils. The modulus variation in a stress controlled cyclic test performed at a rate of one stress cycle per minute is also shown in the figure. The strain rate in this test varied during the test, and is identified at each data point in the graph. The rate of modulus reduction is smaller in this case because the increasing loading rate at higher strains compensates for the modulus degradation with increasing strain. The influence of loading rate on the behaviour of geofoam has been recognized in previous studies based on compression tests (Elragi 2000). Shear modulus values determined by testing small samples are significantly lower than can be inferred from Young's modulus values derived from compression tests on large samples.

The maximum shear modulus G_{max} and Young's modulus E_{max} at very low strains represent upper bound values for these critical parameters but are difficult to obtain from shear or compression tests that rely on direct measurement of deformations. Bender element testing provides a convenient means for evaluating the elastic properties of geofoam by using established relationships between wave velocities and elastic modulus. Shear modulus can be calculated using the shear wave (s-wave) velocity, and Young's modulus can be calculated using the compression wave (p-wave) velocity. Generating s-waves require insertion of elements into the geofoam specimen while maintaining tight contact. The elastic wave velocities in this study were only p-waves. S-wave velocity measurements will be covered subsequently.

Strong signals were received only for waves in the frequency range of 350 to 2000 Hz. The measured travel times at different frequencies of excitation for two identical geofoam specimens are shown in Figure 9. The p-wave velocity was calculated from the travel time and the known height of the geofoam specimen. Except for the lower range of 350-500 Hz, travel times are relatively independent of excitation frequency over 500 to 2000 Hz. For travel times in the wider spectrum of 500 to 2000 Hz modulus values in the range of 22 to 32 with an average of 26 MPa can be estimated. For the slightly larger travel time in the narrow spectrum of 350 to 500 HZ modulus values in the range of 14 to 22 MPa with an average of 17 MPa can be estimated. The cause for this apparent frequency dependence is not known and will be investigated. In general, regardless of this anomaly, these Emax values far exceed commonly quoted modulus values of 3 to 5 MPa for a 20 kg/m^3 density geofoam based on testing of small samples. The E_{max} values derived from bender element testing also form an upper bound for improved modulus estimates of about 10 MPa based on large size samples (Elragi 2000, Elragi et al 2000) and bending tests (Anasthas et al 2001) for the same density geofoam. The bender element modulus results are also in agreement with modulus values derived by back calculation from falling weight deflection tests reported by Duskŏv (1997). It is expected that shear and elastic modulus values obtained using bender elements will yield alternative means of evaluating Poisson's ratio for geofoam. Brocanelli and Rinaldi (1998) have recommended a technique to measure material damping in addition to modulus using bender elements in soils. Extending their frequency domain approach in testing geofoam may provide useful data at low strains. Further comprehensive studies are needed to fully explore the material behaviour at these low strain levels.

SUMMARY

The initial results of an experimental study of the shear behaviour of geofoam are presented. The objective of the test program was to understand the behaviour of geofoam under dynamic loading conditions using controlled laboratory tests. The response of geofoam to shear depends on the loading rate and the density of geofoam and is weaker in strength than for compression loading. The shear modulus in cyclic loading is not influenced by the stress history at low stress levels. However, repeated cyclic loadings under larger shear stress induce softening. The shear modulus of geofoam increases with density and reduces with strain level. The rate of modulus reduction with strain does not appear to be influenced by the density of geofoam. These characteristics of modulus degradation in geofoam are similar to that of soils. Attempts to characterize the response using bender elements is at an early stage, and measured compression wave velocities indicate that E_{max} for 20 kg/m^3 density geofoam is in the order of 20 MPa. Further studies will include detailed characterization of the stress-strain behaviour, and shear wave velocity measurements.

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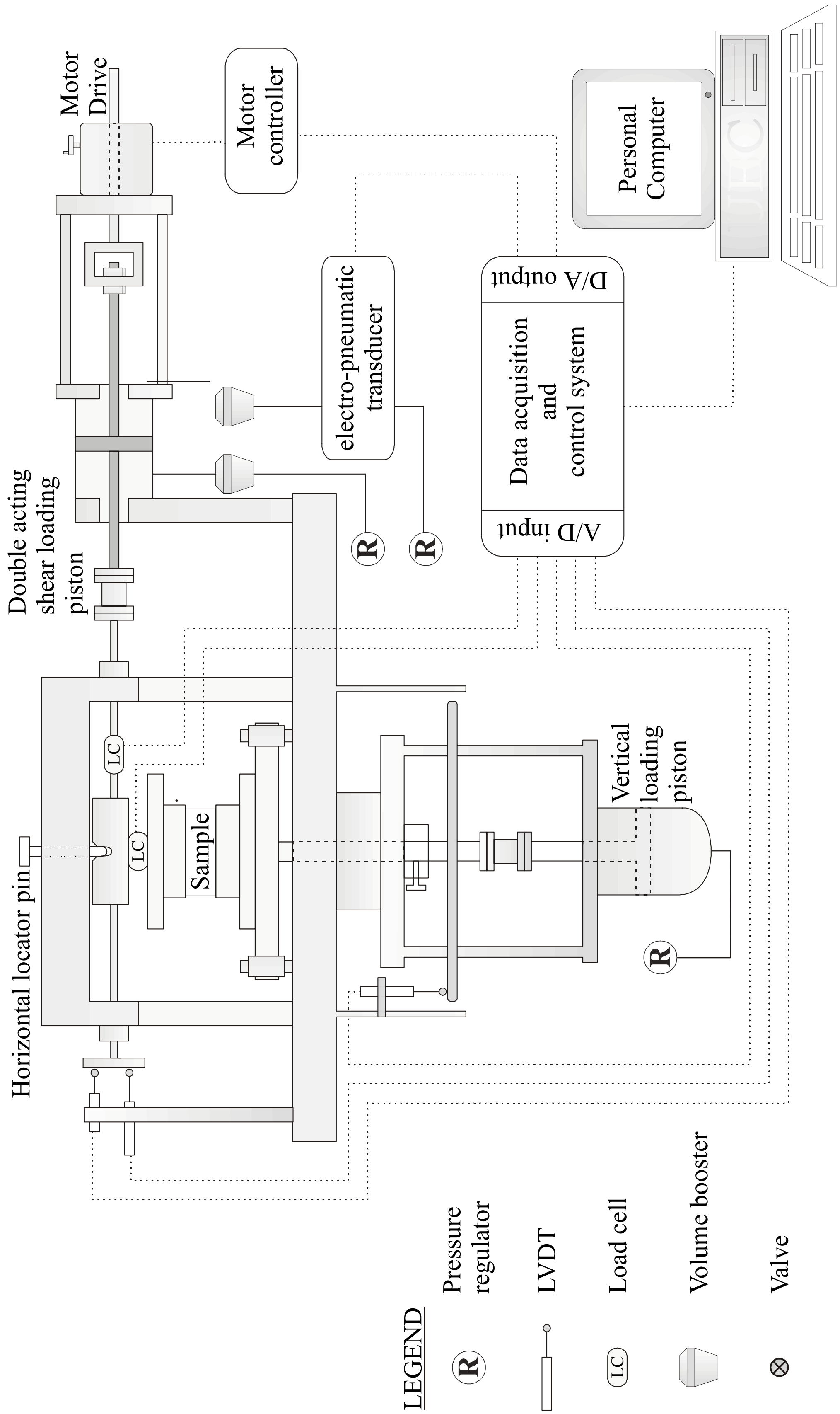

Figure 1: Schematic illustration of the simple shear device

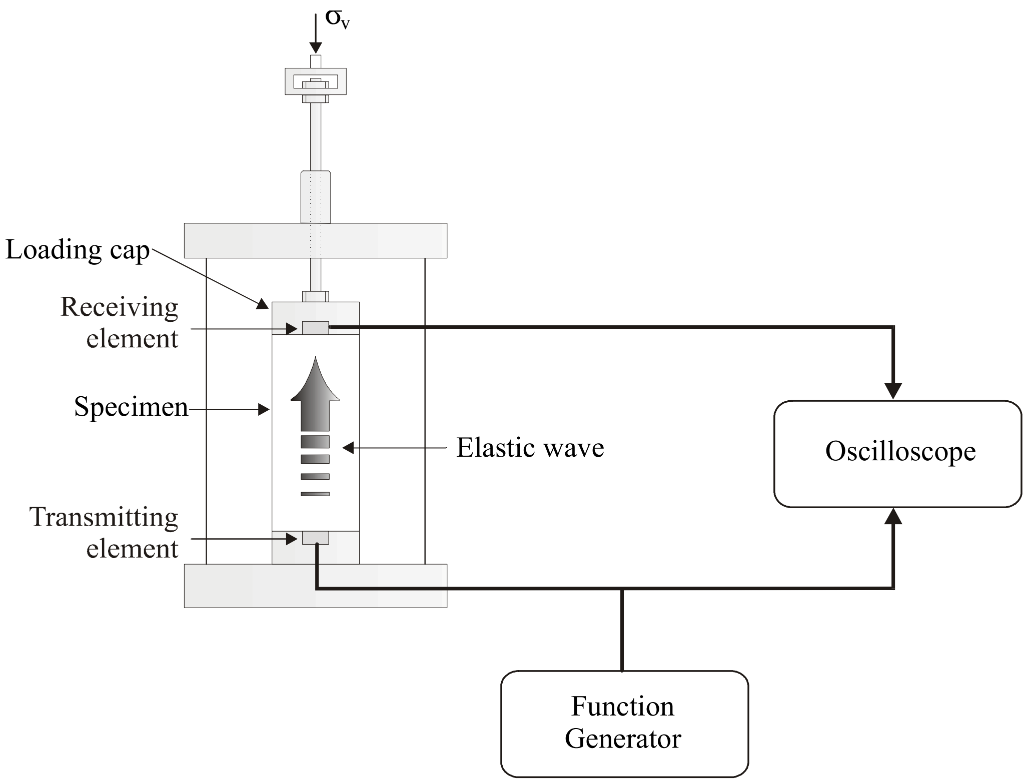

Figure 2: Schematic illustration of the bender element test

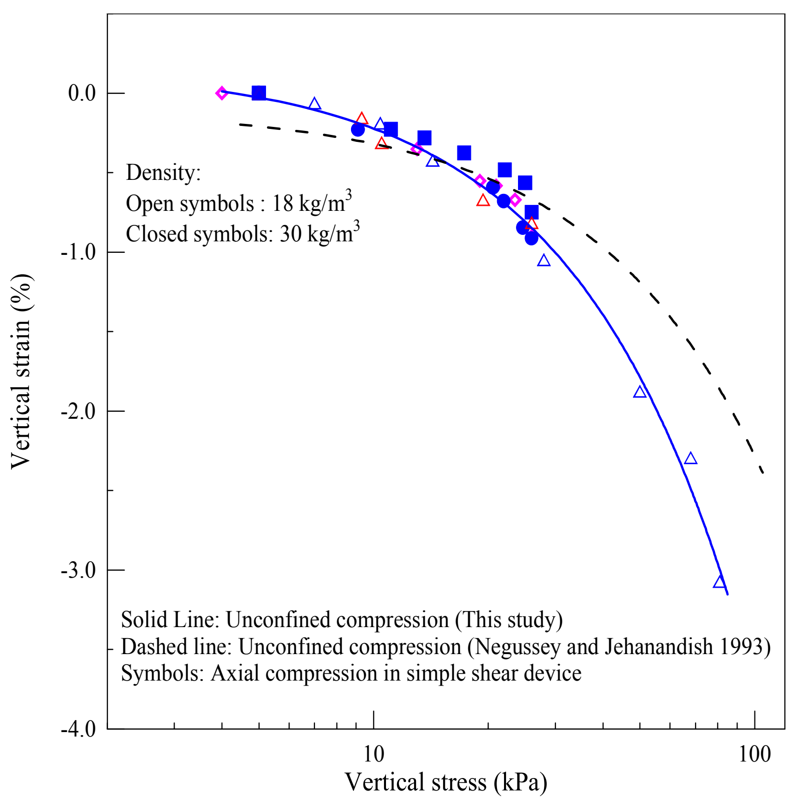

Figure 3: Compressibility characteristics of geofoam

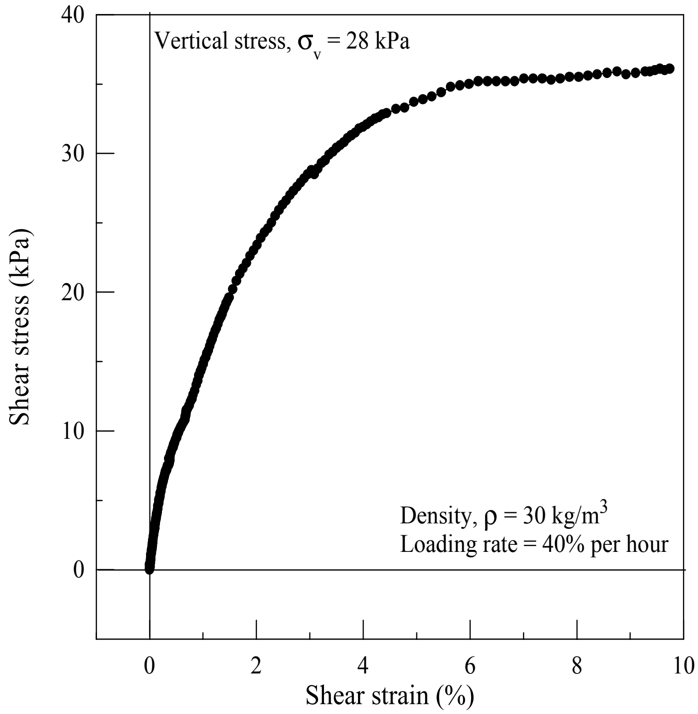

Figure 4 : Shear stress - shear strain response of geofoam.

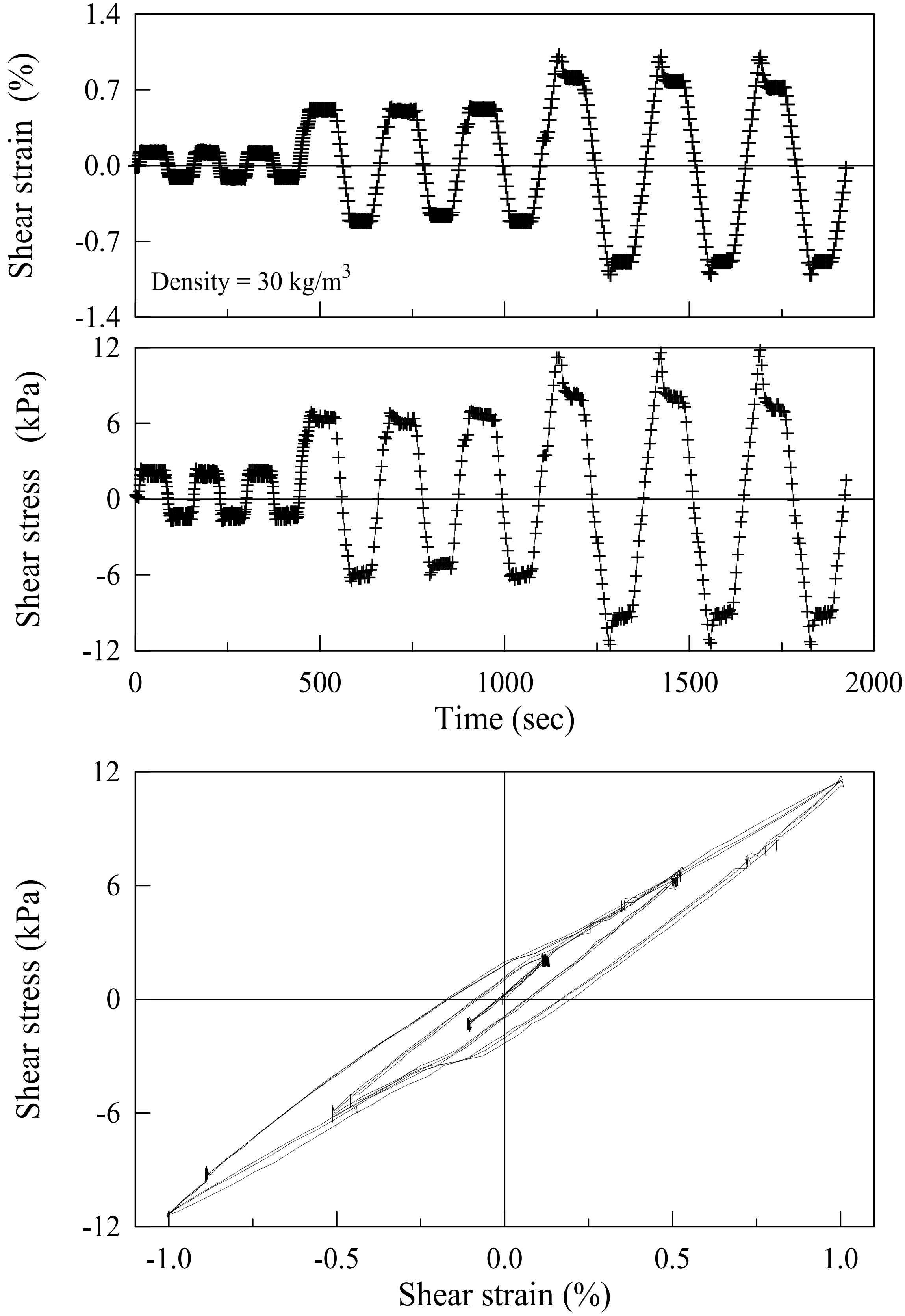

Figure 5 : Stress-strain behaviour of geofoam under displacement controlled cyclic loading

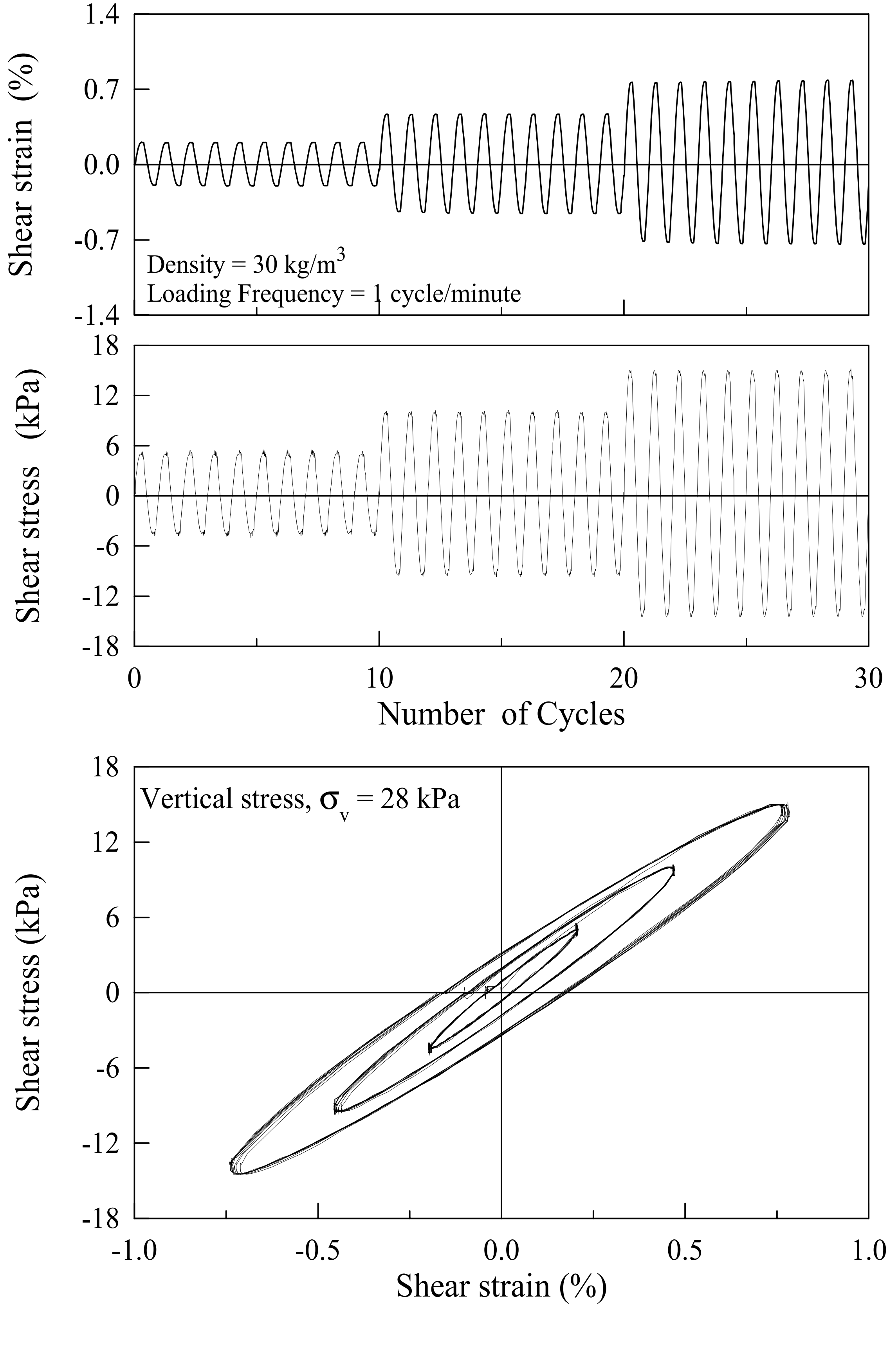

Figure 6: Stress-strain behaviour of geofoam under stress controlled cyclic loading

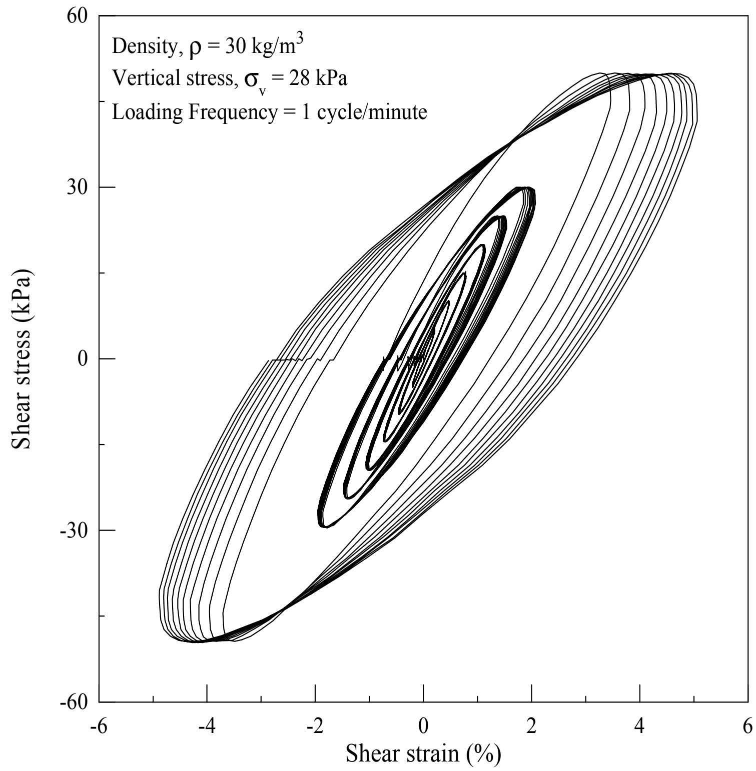

Figure 7 : Cyclic response staged cyclic loading

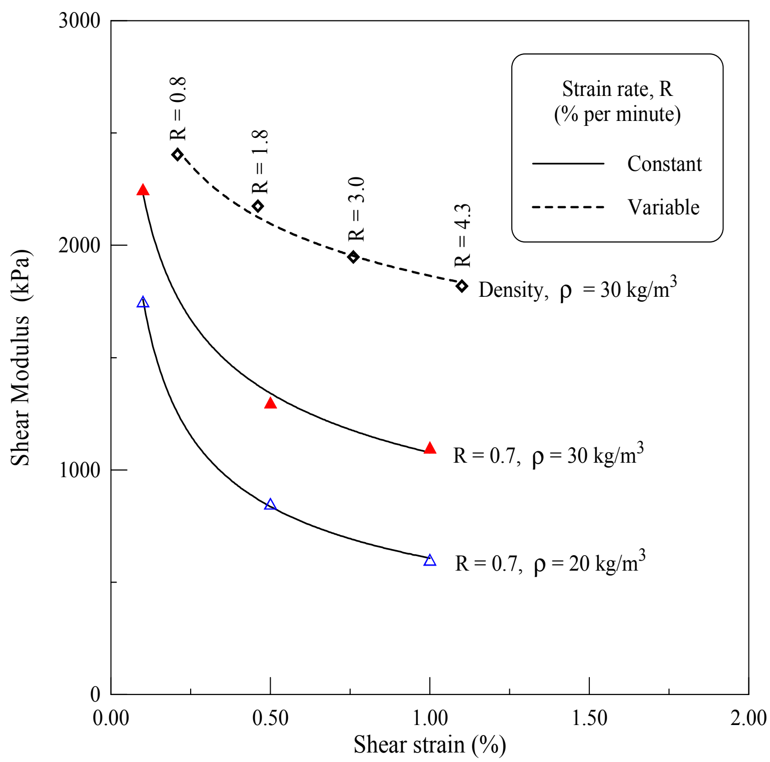

Figure 8: Modulus degradation with shear strain

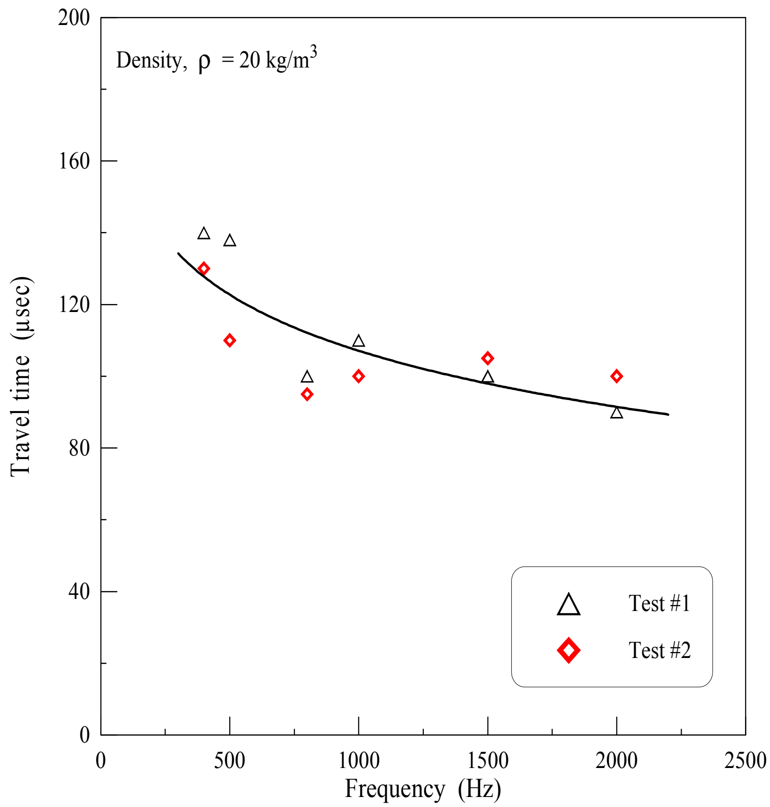

Figure 9: Variation of travel time with the frequency of the p-wave.