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**Geothermal Service
of Canada**

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du Canada**

GEOTECHNICAL BEHAVIOUR OF SAND
CONTAINING A GAS HYDRATE

PHASE I

Department of Civil Engineering
University of Alberta
Edmonton, Alberta

Earth Physics Branch Open File Number 83-9
Ottawa, Canada, 1983

Price/Prix: \$12.00

NOT FOR REPRODUCTION



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Abstract

The first measurements on the mechanical properties of a clathrate hydrate and a hydrate saturated sand are reported. The initial results indicate that the materials are weaker than frozen sand at an equivalent temperature below phase change, but that the shear resistance is higher than for unfrozen sand.

Résumé

Ce rapport présente les premières mesures des propriétés mécaniques des hydrates clathrates et des sables saturés d'hydrates. Les résultats initiaux indiquent que les matériaux sont plus faibles que les sables gelés à une température équivalente, en dessous de la température de changement d'état, et que leur résistance au cisaillement est plus élevée que celles des sables non-gelés.

Final Report
Phase 1 Study of
Geotechnical Behaviour of Sand Containing a Gas Hydrate
DSS Contract 14SU.23235-2-0589
For
Department of Energy Mines and Resources

by
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1 ABSTRACT

A laboratory facility has been established in which gas hydrate saturated sand samples can be prepared, and the stress strain behaviour of these samples studied. Pure hydrate samples as well as sand samples with varying amounts of hydrate have been prepared using Freon 11 as the hydrate former. A facility to study the volume change characteristics of a hydrate saturated sand has also been assembled.

The preliminary strength and deformation results of the hydrate saturated sands illustrate that the material is weaker than frozen sand at an equivalent temperature below the phase change temperature. The hydrate samples have higher shear resistance than the sand in the unfrozen state but the increase is less than 10%. These findings are based on a limited number of tests and in each case the density of the gas hydrate saturated sample was less than the density of either the frozen or unfrozen sand sample. The materials deform in a ductile manner undergoing strains of between 6 to 10% to reach maximum shear resistance.

A capability of measuring the compressional wave velocity through each sample was also developed. The compressional wave velocity measured for pure gas hydrate samples compares well with data reported in the literature on compressional wave velocity measurements in pure hydrate. This shows that the equipment is working.

The behaviour of hydrate saturated samples is similar to that of frozen sand but the bonding of the sand grains by the hydrate crystals is much less effective than by ice crystals. The quantification of these differences requires more experimental data.

2 INTRODUCTION

In Phase 1 of the study on the geotechnical behaviour of sand containing a gas hydrate the aim was to establish a laboratory facility in which the strength and deformation behaviour of hydrate saturated sand could be studied. A system to measure the volume change of a hydrate-saturated sample during decomposition of the gas hydrate was also to be established. A preliminary testing program on a hydrate-saturated sand was also to be conducted to examine how the material behaved under load.

The stress strain characteristics of the sand was studied before and after hydrate saturation of the sand samples. The one dimensional consolidation behaviour of the hydrate sand mixture was studied in one experiment but the results are suspect due to an equipment malfunction.

This report outlines the procedures, and results from the laboratory program. A discussion of the data illustrates how the findings compare with frozen sand behaviour. This is followed with recommendations for further research on sand hydrate material.

3 LITERATURE REVIEW

Appendix A contains a detailed bibliography of recent work (1969 - present) concerning gas hydrates. Interest in problems related to the formation of hydrates in natural gas pipelines and related processing equipment dates back to the mid-1930's. A great deal of experimental information has been accumulated on the formation of hydrates from natural gas components and their mixtures. Recently, the discovery of natural gas in the Arctic and near Arctic regions has renewed the interest in both the theoretical and experimental investigation of gas hydrates, particularly in the ice-gas-hydrate and gas-hydrate regions. No literature however, pertains to the mechanical properties and deformation characteristics of gas hydrate saturated soil, or to the development of gas pressure during hydrate decomposition within a soil.

4 EQUIPMENT ACQUISITION AND CALIBRATION

4.1 Non-Contact Displacement Transducer

To measure the lateral strain of the specimen during hydrate formation or decomposition, KAMAN non-contact linear displacement transducers (Model 12CU) were employed. The transducers send out an electronic eddy current which is reflected back by metal surfaces attached to the sample surface. The transducers were mounted on the cell by means of removable brackets which allowed measurements to be taken at various sample locations. Strips of aluminum foil were attached to the sample to serve as a reflective surface. These surfaces deformed with the sample during the experiments allowing the lateral deformation to be measured.

4.2 Flowmeter

A power supply for the flowmeter transducer was obtained and the unit was calibrated. It was used to monitor and record gas flows during hydrate decomposition in the one dimensional volume change experiments. When the unit was ordered the rates of gas flow that occurred during decomposition were not known. A unit rated at 0 - 500 cm³/min. was obtained, however during initial testing the gas flows encountered exceeded the capacity of the unit. Further work will require a flowmeter with greater capacity.

4.3 Backpressure Regulator

The backpressure regulator has proven to be effective in maintaining constant pressure during hydrate decomposition. One drawback of the unit is that it is rated at 3500 kPa maximum pressure. For this study using Freon-backpressures of 242-345 kPa were used. Since pressures of this magnitude are in the lower 10% capacity of the backpressure regulator some non-linearity in its performance is recorded.

4.4 Load Cell

The load cell was calibrated and performed satisfactorily throughout the testing program.

4.5 Pressure Transducers

The pressure transducers, used during the one dimensional volume change tests, were found to be influenced by temperature differences. This problem will be corrected by the manufacturer before further testing is undertaken.

4.6 Combustible Gas Detector

A combustible gas detector and alarm system was installed in the cold room. The unit has been calibrated for propane gas.

4.7 Acoustical Transducer

The acoustical transducers were designed by Structural Behaviour Engineering Laboratory. They are 5.08 cm in height and 3.17 cm in diameter. The transducers are designed to measure compressional (P) and shear (S) wave velocities sequentially on the same specimen. They have been constructed in such a manner so that they are mounted within the upper and lower load platens of the triaxial cell.

4.8 Equipment Modification

In order to test the mechanical and acoustical properties of hydrate saturated sand at various temperatures, several modifications had to be made to the standard triaxial cell. Figures 1 and 2 show the triaxial cell used during the experimental program. Plastic cooling coils connected to an external temperature bath were employed to maintain temperatures within the cell. Plastic cooling coils were used to allow the eddy currents from the non-contact displacement transducers to pass through them.

The major modification to the triaxial cell was the incorporation of sonic transducers into the top and bottom load platens. Figure 3 illustrates the top platen with an enclosed transducer. The transducers were built out of high strength steel and are capable of withstanding loads up to 89 kN. In order to connect the transducer with equipment outside of the cell, the signal cable were enclosed in plastic tubing and sealed with Swagelok fittings at the

transducer and the bottom of the triaxial cell.

The increased height of the load platen necessitated an extended triaxial cell. This was accomplished by inserting a 15 cm aluminum extension to the cell wall as shown in Figure 2.

A fan was installed in the cold room to facilitate the removal of combustible or toxic gasses. In addition, further modifications were required to accommodate a triaxial loading frame in the controlled environment room and also for the combustible gas to be removed.

5 LABORATORY INVESTIGATION

5.1 Introduction

The laboratory investigation was planned to establish how the behaviour of gas hydrate saturated sands compare with frozen sand and to provide direction for the future testing of the material. Several objectives were set at the beginning of the investigation to provide an overall and continuing perspective to the work:

- a. The first was to study the mechanical behaviour of hydrate saturated sands;
- b. The second objective was to observe and quantify the behaviour of decomposing hydrate saturated sands.

In the compression testing of the hydrate saturated sand it was initially planned to follow a simple isotropic stress path, so that, as few variables as possible complicated the response of the hydrate saturated material. The material behaviour is described in terms of total stress to compare it with published ice-sand data. A continuation of the study should include the influence various stress paths have on the behaviour of the hydrate saturated sand.

5.2 Soil Materials

The choice of sand for the testing program was made considering the composition of Beaufort Sea sediments. The soil used in all tests was a fine mortar sand obtained locally. Figure 5 illustrates a typical grain size curve for

this material. A maximum and minimum density test was performed using standard procedures outlined in ASTM D 2049. The maximum and minimum dry density of 1730 kg/m³ and 1420 kg/m³ respectively was obtained by this method. Considering the sand has a specific gravity of 2.678, these densities correspond to porosities ranging from 35% to 47%.

5.3 Choice of Hydrate-Forming Material

Field applications require experimental data on gas hydrate formed from natural gas. The composition of the gas would have to reflect the composition of the natural gas found in the Canadian Arctic. The decision to perform experiments on another form of gas hydrate was based on the need to work at high pressure, i.e. approximately 7000 kPa, during the formation of a natural gas hydrate. Table 1 is a short list of some of the known hydrate formers and their critical temperature and pressure (Cheng and Pinder, 1976).

Freon 11 was chosen for this study because it forms a hydrate at low pressure and warm temperatures, and the fact that it is not toxic, flammable or corrosive made it safe to work with. The high critical decomposition temperature and low critical decomposition pressure for Freon 11 allows for formation of hydrate above 0°C at atmosphere pressure. This allows dependable hydrate formation in the laboratory and ease of handling of the sand-hydrate specimens during the experimental set-up. The physical characteristics of Freon 11 and its pure hydrate are presented in Table 2.

Under ideal conditions, the composition of the Freon 11 hydrate is 16.6 moles of water to one mole of Freon 11. The equivalent Freon 11 volume is 23.9%. In practice it is difficult to achieve this ratio exactly; one of the two components is likely to be in excess of these amounts (Cheng and Pinder, 1976).

5.4 Sample Preparation of Sand and Sand Hydrate Mixture

The samples of sand without hydrate were prepared by placing a double latex membrane around the bottom load platen of the triaxial cell and sealing them with an O-ring. A split mold was strapped around the bottom platen and a sand-water slurry was poured through a funnel into the mold. Suction was then applied to the sample via the base loading platen, which removed excess pore fluid from the sample. The top load platen and drainage line were then attached and the split mold was removed after the suction had imparted some strength to the sand sample. The sample dimensions were recorded, the cell was filled with silicon oil, and a nominal cell pressure was applied to the cell and sample. The suction applied to the sample was then disconnected since the sample now had some strength due to positive effective stress between the sand grain.

The hydrate saturated samples were prepared in a mechanical mixer. Premeasured quantities of Freon 11, water and sand were allowed to cool for several hours in a temperature controlled room. The Freon 11 was slowly added

to the mixer while the sand and water were being stirred. When the three compound mixture became stiff, indicating hydrate crystals had formed, it was transferred to the same split mold as was used to prepare the sand only samples. The sample was then left at $+1^{\circ}\text{C}$ for a minimum period of five hours or until it exhibited a hard consistency.

5.5 Pure Hydrate Formation

Propane hydrate has been formed in a plexiglass pressure chamber. The method used involved the agitation of liquid propane and water at $+2^{\circ}\text{C}$, under a pressure of 600 kPa. This method quickly produces white flaky hydrate crystals. When agitation of the emulsion was terminated the hydrate flakes rose to the top of the excess water and form a solid mass within a few hours.

Freon 11 hydrate has also been formed in the mixing vessel by a similar method. During the initial formation testing of pure Freon 11 hydrate it was found that varying the ratio of water to Freon 11 induces the formation of hydrates with different physical properties. If the liquid Freon 11 to water ratio was in excess of 0.239, the resulting hydrate was snowlike in appearance. Conversely, if the above ratio was less than 0.239 the hydrate was ice-like in appearance. This is similar to the finding of Pandit and King (1982) on propane hydrates.

A sample of pure Freon hydrate was formed. The procedure to form the pure hydrate sample followed the same

procedure as given above for the hydrate sand samples. After the water and Freon 11 were thoroughly stirred in the mechanical mixer, the mixture was placed in a one dimensional freezing apparatus (Sego et al., 1982). The mixture was then cooled to initiate crystal formation and allow the sample to cool one dimensionally from the base upward. This allows any expansion or contraction of the sample to occur without any thermal cracking.

Figure 4 shows a specimen of pure hydrate formed in the laboratory. The sample was prepared in the laboratory with a Freon 11 to water ratio of 0.239. During the one dimensional cooling of the sample, the hydrate with a Freon 11 to water ratio greater than 0.239, settled to the bottom of the mold. The resulting hydrate at the bottom of the sample resembles compacted snow (illustrated on the left side of Figure 4); whereas, hydrate formed at concentrations lower than 0.239 have a hard ice-like appearance (illustrated on right side of Figure 4). To properly form a homogeneous sample of pure hydrate both agitation and rapid cooling are required through the crystal formation. Then the crystals would have to be compacted and the sample allowed to solidify.

A series of experiments were conducted in which a hydrate-water emulsion was transferred to a sand sample under positive pressure. This method of hydrate saturation proved ineffective however, since a solid hydrate plug would form rapidly at the base of the sand sample and in the bottom platen. This effectively seals off any additional

mass movement of hydrate-water emulsion into the sample.

5.6 Experimental Procedure

5.7 Triaxial Testing

Once the Freon 11 hydrate specimen had been solidified after cooling it was removed from the mold. Its dimensions were measured and then it was mounted in the triaxial cell. The sample was surrounded by a 1 mm thick neoprane membrane and sealed to the platens with Viton O-rings. The cell was filled with DC200 silicone fluid and the system was allowed to warm to the test temperature of $+2.0^{\circ}\text{C}$. Initial compression and shear wave velocities were recorded at this time. The shearing of the sample was conducted using the following steps:

1. The loading ram was allowed to come in contact with the load cell attached to the reaction frame. This allowed zero deviatoric load to be recorded on the data acquisition recorder.
2. The movable loading platen of the testing machine was adjusted to bring the sample in contact with the loading ram.
3. A small seating load was applied to ensure contact. The LVDT (linear variable differential transformer) was adjusted to its zero position for the experiment.
4. The displacement rate determined for this sample was set on the machine.

5. The zero parameter pressure, LVDT, and load cell readings were recorded.
6. The machine was started, thus applying a constant rate of deformation to the sample.
7. At appropriate time intervals the load cell and LVDT measurements were recorded.
8. The loading of the sample was continued until the sample had undergone a large strain, i.e., greater than 8% or the more usual case, until the resistance of the sample had begun to decrease.
9. At this point the loading was terminated.
10. The sample was disconnected from the pressure systems.
11. The cell was dismantled, and the sample removed. The dimensions were determined.
12. The total specimen was now used to evaluate the final moisture content of the sample.

5.8 One-Dimensional Volume Change Tests

The one-dimensional volume change tests were conducted using a modified Rowe Consolidation Cell shown in Figure 6. The cell is composed of an upper and a lower chamber separated by a loading ram and sealed with a rubber diaphragm. For the purpose of this testing program the two chambers were isolated from one another. Figure 7 shows the one-dimensional volume change setup. Pressure transducers are connected to the top and the bottom chamber of the cell.

Sand with a water content of approximately 10% was placed in the lower chamber. A normal load was applied to the sample by a Bellofram rolling diaphragm cylinder which is mounted above the sample. Vertical measurements were obtained by an LVDT which was attached to the axial loading ram. When consolidation of the sample was completed, it was cooled down to approximately $+1.5^{\circ}\text{C}$. A temperature measuring RTD mounted at the top of the sample provides accurate temperature monitoring. Freon 12 gas at a pressure of 241.5 kPa is then allowed access to the top and the bottom chambers of the cell. The hydrate was then allowed to form within the sand sample for a period of 5 days. Pressure and displacement changes were recorded during this formation period.

After 5 days a flowmeter and backpressure regulator were connected (see Figure 7) to the sample access port at the base of the cell. The back pressure regulator was set at 483 kPa. Above this pressure, any excess gas would bleed off and be measured by the flowmeter. The top pressure chamber remains at 241.5 kPa. Decomposition of the hydrate is effected by one-dimensional thawing produced by circulating hot water through a heating plate at the bottom of the consolidation cell. Changes in pressure, displacement and temperature are electronically recorded. The flowmeter attached to the cell base is monitored and recorded on a portable X-Y plotter. This allows for a continuous record of the output data.

6 LABORATORY RESULTS

6.1 Triaxial Compression Test Results

The deviatoric stress versus strain curves for triaxial samples are shown in Figures 9 to 14. Figure 15 is a p-q plot which contains the strength data at failure for all the compression tests. Table 3 summarizes the physical properties of the test samples and Table 4 is a summary of the compression test results at failure.

The terminology used in presenting the results and used in the discussion of results will be briefly explained. The deviator (deviatoric) stress is the stress difference between the maximum applied and the confining stress. Strain is the engineering definition which is the change in length divided by the original length. A p-q plot is a plot on which data at failure within a sample is plotted and defined:

$$p = (\sigma_1 - \sigma_3)/2$$

$$q = (\sigma_1 + \sigma_3)/2$$

The void ratio is defined as the volume of the void space divided by the volume of the soil solids. The "% sand by volume" is the volume of the sand particles as a percentage of the total volume of the soil (includes volume of voids and soil solids). In presenting the laboratory results the term "25% hydrate" is used. This is based on the % hydrate (total weight of water + hydrate former) as a percentage of the dry weight of soil used to prepare the sample.

Figure 9 shows the stress strain curves for the sand without hydrate samples. The data show a strain hardening behaviour typical of a loose sand. The addition of 25 % hydrate has little effect upon the behaviour of the sand hydrate material (Figure 10). Increasing the hydrate content to 50 % shown in Figure 11 again appears to have little influence upon the maximum deviator stress recorded during the experiments. Unfortunately the tests at 75 % and 100 % hydrate were terminated due to leaks in the membranes during the experiments.

Figure 12 compares the results of sand with various hydrate percentage at a confining pressure of 345 kPa. No trend in the strength behaviour can be recognized from these data plots. The 50 % hydrate sample failed at a lower deviatoric stress and has a much lower initial stiffness than the 25 % and 40 % samples. It is suspected that free water existed in this sample. This observation is supported by the compressional wave velocity data (Table 5) which shows that the 50% hydrate sample had a low p-wave velocity. The compression test results in Table 4 indicate that the addition of hydrate slightly increases the strength of the sand above its value with no hydrate.

Normally, the samples were allowed 12 hrs to come to temperature before testing. Testing of the 50% hydrate sample at 206 kPa confining pressure was delayed for 48 hrs due to an equipment malfunction. At failure, this sample achieved deviator stresses similar to the sample tested at

345 kPa confining pressure. This suggests that the hydrate-sand increases in strength due to aging. Stoll and Bryan (1979) suggest that there is a formation and growth of bonds between the hydrate particles with time. It should be noted that a slight increase in wave velocities were also recorded for this sample (Table 5).

Figure 13 shows the stress strain curve for a pure hydrate sample. The sample attained a maximum stress at failure similar to the sand mixtures, however, a pronounced ductile behaviour was recorded with the sample failing a 14.4 % strain.

For comparison purposes a frozen sand sample was tested at -6.0°C at the same strain rate as the other experiments. Figure 14 shows that this sample attained a maximum deviator stress about 10 times that of the sand hydrate sample. It should be noted that this sample was tested below 0°C but at a similar magnitude of temperature below the phase change temperature of the hydrate samples. All the sand hydrate samples were tested at a temperature of $+2^{\circ}\text{C}$.

Figure 15 is a p-q plot that summarizes all the failure data of the samples tested. The samples of sand without hydrate have a angle of internal friction (ϕ) of 34.4° and no cohesion. The hydrate samples do not vary significantly from this failure envelope. The plot indicates that the hydrate may impart a small cohesion to the sand but the failure resistance is similar to sand without hydrate.

6.2 Velocity Measurements

Table 5 presents a summary of the wave velocity measurements obtained during the testing program. The P wave arrival times were easily determined with great precision whereas the S waves were at times difficult to establish.

The P wave velocities of the hydrate sand samples ranged from 1.35 to 2.14 km/sec, a significant increase over the no hydrate sand P wave velocity of 1.01 km/sec. The P wave velocity for the solid hydrate sample was 2.54 km/sec. These data are in good agreement with the velocities measured by Pandit and King (1982) and Stoll and Bryan (1979) on propane hydrate.

The p wave results are plotted versus applied confining pressure in Figure 16. This shows that the p wave velocities are slightly sensitive to increased confining pressure and also to the % of hydrate present within the sample. It should be noted that the 50% hydrate samples have higher p-wave velocities than the 25% hydrate sample at both 69 and 206 kPa confining pressure. At 345 kPa confining pressure the p-wave velocity of the 50% hydrate sample is substantially less than the 25% hydrate sample. The result is questioned since the strength of the 50% hydrate sample shown in Figure 12 at a confining stress of 345 kPa is less than those at different % hydrates. It is anticipated that this sample developed a zone of non-solid hydrate resulting in a decreased p-wave velocity and a slightly reduced deviator stress at failure.

The S wave velocities ranged from 0.73 to 1.19 km/sec and clearly are dependent on the hydrate content of the soil. The S wave velocities generally increase with increasing hydrate content and approach the S wave velocity recorded in the pure hydrate sample.

6.3 One dimensional volume change

Only one test was completed due to several problems with the equipment. The most serious problem was that the pressure transducers were not temperature compensated and the readings fluctuated with temperature changes. During hydrate decomposition, therefore, the pressure readings were inaccurate.

The flowmeter did register some outward flow of Freon 12 gas during decomposition. The flows were much higher than expected and rapidly exceeded the limit of the flow meter. Figure 17 shows part of the continuous X-Y plotter record of gas outflow. It can be seen that the flowmeter registered a sudden outflow of gas from the sample. This is similar to the gas kick reported by Davidson et al. (1978) and suggests that the hydrate decomposes at a rapid rate once decomposition conditions are achieved.

7 DISCUSSION OF LABORATORY RESULTS

In the following section the measured laboratory results will be discussed with the emphasis on how the results compare with frozen sand results in the literature. The comparison with frozen sand is being made since data on their behaviour exists in the literature (Goughnour and Andersland, 1968; Alkire and Andersland, 1973; and Sego et al, 1982). This comparison will also help to direct future experimental programs.

A difficulty in making the comparison is the fact that all the strength experiments were performed at $+2.0^{\circ}\text{C}$ which is 6.3 degrees below the formation temperature of Freon 11 hydrate at atmospheric pressure. The frozen sand data in the literature is predominantly at temperatures of $6-10^{\circ}$ below the melting point of water. It must be noted that all the experiments in this research program were conducted at the temperature that allowed any free water in the sample to exist as water, not ice. The frozen sand samples reported in the literature have no free water at the test temperatures.

The strength results of the hydrate saturated sands when plotted in Figure 15 suggest that the addition of the hydrate crystals does not alter the strength. This is in contrast to the ice bonding provided to the sample of sand frozen and tested at -6.0°C . The frozen sand sample had a deviator stress at failure of 3500 kPa, compared to 167, 247 and 241 kPa deviator stress at failure measured for the no hydrate, the 25% hydrate and the 50% hydrate samples. This

shows that the bonding provided by the gas hydrate crystals is small compared with that provided by the ice crystals.

The strength of polycrystalline ice at -6°C under a slight confining stress and at a strain rate of approximately 0.5%/hour is 2000 kPa as reported by Michel (1978). This is in comparison to 920 kPa measured for pure Freon 11 and given in Table 4. The reduced strength measured for the 25% and 50% hydrate sample could be partly due to the reduced strength of the hydrate bonds compared to the ice bonds. It is assumed that the bond strength in both pure hydrate and ice will be proportional to the compressive strength of the material. It also must be noted that the total measured strength reduction is not only due to this reduced bond strength.

The strength of a cohesionless material in the thawed state is dependent on the void ratio of the sample. The 25% and 50% hydrate samples have void ratio between 30% and 81% higher than the samples tested in the thawed state and between 95% and 167% higher than the sample tested frozen.

The increase in void ratio of the hydrate sample above those in the thawed state suggest that for the samples with the high void ratio to have the same strength as a sand with a lower void ratio some strength or bonding must be contributed by the hydrate crystals which bond the sand particles and fill the void space. This suggests that a slight cohesion exists within the hydrate-saturated sand but that the friction angle of the sand may be lower than that

of the sand in the thawed state.

Figure 18 shows the conventional Mohr plot of the data of the no hydrate, 25% hydrate and the 50% hydrate samples at failure. The following cohesion (c) and angle of internal friction (ϕ) fit the laboratory data:

Material	c kPa	ϕ (°)
No hydrate	0	34.4
25% hydrate	40	31.5
50% hydrate	40	36.0

This preliminary data would suggest that both the cohesion and the angle of internal friction is influenced by the amount of hydrate present. More data is required at each % hydrate to establish the influence of both % hydrate and the void ratio on the strength of the material.

Figure 19 shows the results of experiments conducted by Alkire and Andersland (1973) in which the influence of void ratio on the strength of frozen sand is illustrated. As the void ratio increases the deviator stress decreases and the strain to failure increases. The data in Table 4 illustrates that the strain to failure increases in samples with high void ratio at the same confining stress. The deviator stress, however, does not decrease with increased void ratio as was found in frozen sand by Alkire and Andersland (1973).

Goughnour and Andersland (1968) showed that the peak strength of a frozen sand at constant temperature and strain rate varied with the % sand by volume. They found that above

approximately 42% sand by volume a rapid increase in shear strength is found with an increase in % sand by volume. Figure 20 shows the influence of % sand by volume on the strength of Ottawa sand at different temperatures and strain rates. Figure 21 contains the results from this experimental program and illustrates that to a % by sand by volume of 50% the limited data shows no influence at each different confining stress.

The compressional wave velocity measurements given in Figure 16 and Table 5 compare closely with those presented by Pandit and King (1982) for the Hydrate 1 sample. Their result shows that above 0°C Hydrate 1 has a velocity of approximately 2.05 km/sec. In this study at +2.0°C the pure Freon 11 hydrate had a velocity of 2.54 km/sec and a density of 890 kg/m³ compared to 850 kg/m³ for the Hydrate 1 sample of Pandit and King (1982). The higher velocity is contributed to the slightly increased density and different hydrate former used in the two studies.

Figure 16 summarizes the p-wave velocities measured in this experimental program. The increase in velocity with applied pressure is expected. The sample at 50% hydrate and 345 kPa confining stress must have an error associated with its measurement or water within the sample which is not bonded in hydrate crystals. The fact that the p-wave velocity increases with percentage hydrate between 25 and 50% and then decreases as the % hydrate increases to 75 and 100% cannot be explained at this time. It was anticipated

that as % hydrate increased the p-wave would also increase,
but above 50% hydrate the density may dominate the
measurement.

8 CONCLUSIONS

Phase 1 of the program on the study of the geotechnical behaviour of sand containing a gas hydrate has resulted in a laboratory facility that can test both the strength and deformation properties of the hydrate saturated sand. The compressional wave velocity through the sample can also be evaluated as the sample is being loaded. Equipment is also available to measure the one dimensional volume change characteristics of hydrate saturated sand.

The preliminary laboratory evaluation of the equipment and hydrate saturated sand indicated the following:

1. The strength in triaxial compression of a hydrate saturated specimen is just slightly higher than the unfrozen sand.
2. The hydrate samples deformed in a more ductile manner than the unfrozen sand samples.
3. The void ratio of the hydrate samples tested were much higher than the unfrozen sand samples and the influence of this could not be evaluated due to lack of sufficient data.
4. The hydrate samples are much weaker than frozen sand samples at comparable temperatures.
5. The p-wave velocities measured are comparable with data reported by Pandit and King (1982).

9 RECOMMENDATION FOR FUTURE RESEARCH

The establishment of the testing facility and the findings from the Phase 1 study suggest the following for future research on the geotechnical behaviour of sand saturated with a gas hydrate:

1. *Pure gas hydrate*

- a. A study of the P and S wave velocities of a sample at a constant temperature over a wide range of confining pressure.
- b. A study of the P and S wave velocities of a sample at a constant confining pressure and over a temperature range of -20°C to $+10^{\circ}\text{C}$.

These will provide information on the influence of each variable on the P and S wave velocities. This should be conducted on pure hydrates formed from the following hydrate formers to provide a range of values for different gas hydrates:

- 1) Freon 11
- 2) Freon 12
- 3) Propane
- 4) Methane
- 5) Natural Gas

2. *Gas hydrate saturated sand*

- a. The influence of confining pressure on the strength and deformation of samples with various percentages of hydrate.
- b. Study the influence of sample density on the

strength and deformation of a hydrate saturated sample.

- c. Study the influence of varying the strain rate and the temperature on the strength and deformation properties of a hydrate saturated sample at a uniform density.
- d. Study the one dimensional deformation characteristics of a hydrate saturated sample at a uniform density.

This will provide information for the evaluation of the influence that hydrate saturated sands will have on a production well operating within these materials.

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Table 1

Hydrate Formers

Hydrate Former	Critical Temperature (°C)	Critical Pressure (kPa)	Mol H ₂ O to Mol of Former
Ethane	14.5	527.0	8.25
Propane	5.7	522.4	18.0
Cyclopropane	17.0	596.0	17
Freon 11	8.3	87.2	16.6
Freon 12	9.9	428.7	15.3
Freon 21	8.7	101.4	16.8
Freon 31	17.9	286.8	8.0
Freon 40	20.4	486.5	7.2
Freon 40B1	14.7	153.0	7.9
Freon 142b	13.1	232.1	17
Hydrogen sulfide	29.6	2230.0	6

Table 2

Properties of Freon-11 and its hydrate

Formula	CCl ₃ F
Molecular Weight	137.36
Cost (per 5 gallon)	\$47.15
Normal Boiling Point	23.8°C
Liquid Density at Normal Boiling Point	1.46 gm/ml
Critical Temperature	198°C
Critical Pressure	4378 kPa
Solubility in Water	Practically Insoluble
Molecular Volume (at b.p.)	92 ml.
Odor	Faint ethereal
Flammability	Non-Flammable
Toxicity	Less Toxic than CO ₂
Hydrate Composition	16.6 mol H ₂ O/mol F-11
Hydrate Crystal Structure	Type II
Calculated Crystal Density	1.15 g/ml
Hydrate Critical	8.28°C
Decomposition Temperature	
Hydrate Critical	87.6 kPa
Decomposition Pressure	
Heat of Reaction	
M(g) + nH ₂ O = M·nH ₂ O	148.3 KJ/mol

Table 3
Physical properties of test samples

Sample	Total Density (kg/m ³)	Dry Density (kg/m ³)	Void Ratio	% Sand by Volume (%)
No Hydrate	1600	1460	0.83	54.6
No Hydrate	1590	1440	0.86	53.8
No Hydrate	1600	1460	0.83	54.6
25% Hydrate	1670	1280	1.09	47.9
25% Hydrate	1560	1240	1.16	46.3
25% Hydrate	1590	1310	1.04	49.0
25% Hydrate	1570	1120	1.39	41.8
50% Hydrate	1760	1060	1.52	39.7
50% Hydrate	1620	1110	1.41	41.5
50% Hydrate	1750	1160	1.30	43.5
75% Hydrate	1600	960	1.78	36.0
100% Hydrate	1540	770	2.47	28.8
Pure Hydrate	890	-	-	0.0
Frozen Sand	1952	1595	0.56	64.1

Table 4
Summary of compression test results

Sample	Void Ratio	Confining Pressure (kPa)	Deviator Stress @ Failure (kPa)	Strain @ Failure (%)
No Hydrate	0.83	69	167	11.71
No Hydrate	0.86	206	541	11.48
No Hydrate	0.83	413	1136	16.77
25% Hydrate	1.09	69	247	8.41
25% Hydrate	1.16	206	474	6.78
25% Hydrate	1.04	345	864	9.46
25% Hydrate	1.39	345	1006	8.19
50% Hydrate	1.52	69	241	10.0
50% Hydrate	1.41	206	778	6.57
50% Hydrate	1.30	345	808	10.13
75% Hydrate	1.78	345		
100% Hydrate	2.47	345		
Pure Hydrate	-	345	921	14.29
Frozen Sand	0.56	70	3500	3.00

Table 5
Velocity measurements

Sample	Confining Pressure (kPa)	% Sand by Volume (%)	P-wave (km/sec)	S-wave (km/sec)
No Hydrate	413	53.8	1.01	0.46
25% Hydrate	69	47.9	1.56	0.73
25% Hydrate	206	46.3	1.69	0.85
25% Hydrate	345	49.0	2.14	1.07
50% Hydrate	69	39.7	1.69	0.92
50% Hydrate	206	41.5	2.03	0.88
50% Hydrate	345	43.5	1.35	0.92
75% Hydrate	345	36.0	1.85	1.01
100% Hydrate	345	28.8	1.69	1.09
Pure Hydrate	345		2.54	1.01

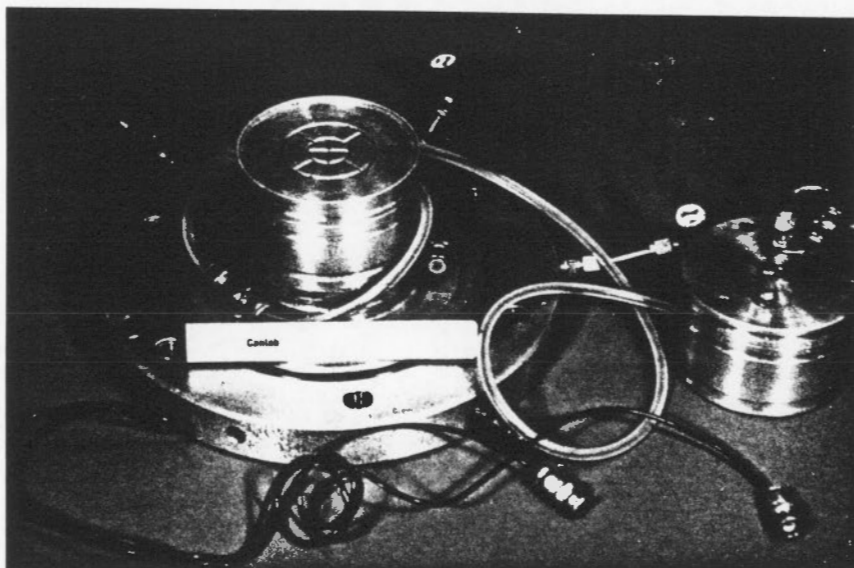


Figure 1 Triaxial cell base and load platen with enclosed acoustic transducers.

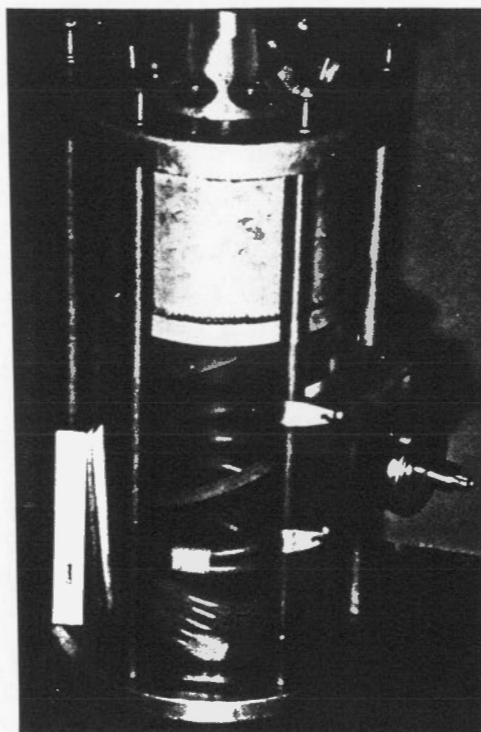


Figure 2 Modified triaxial cell with plastic cooling coils and non-contact displacement transducers.

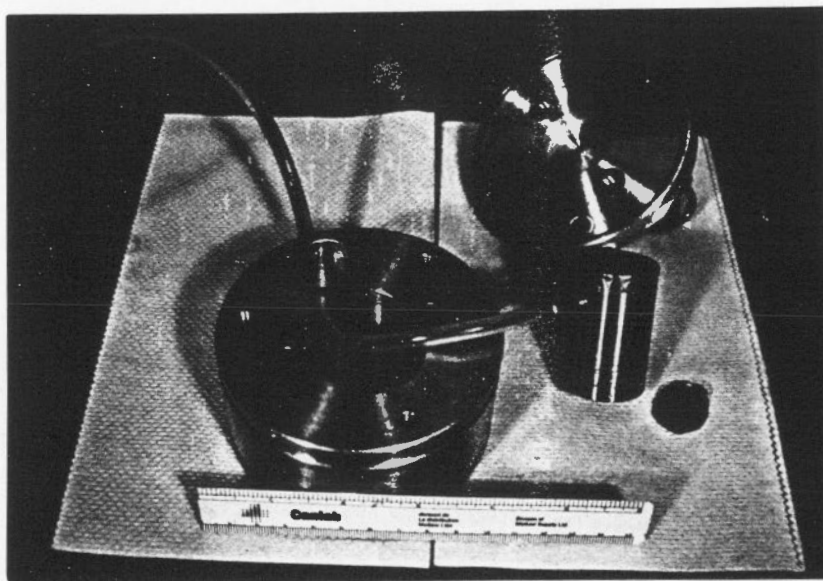


Figure 3 Top load platen with acoustic transducer.

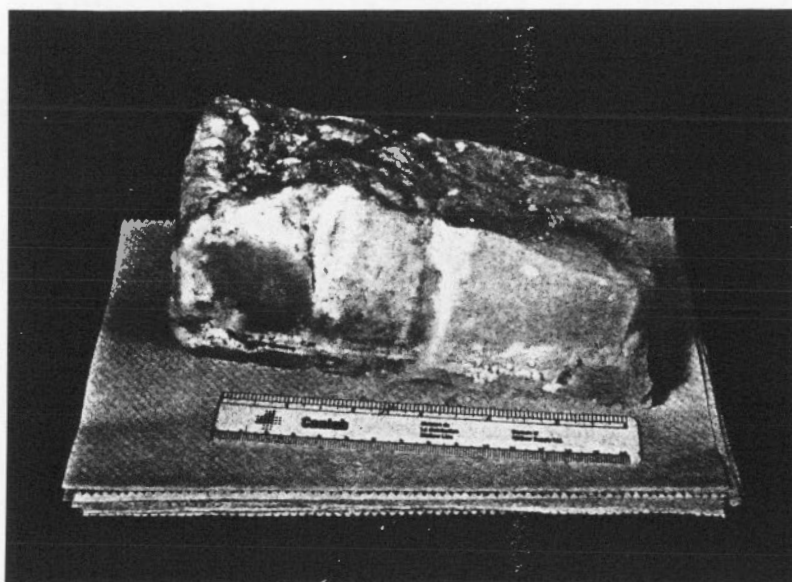


Figure 4 Pure hydrate sample.

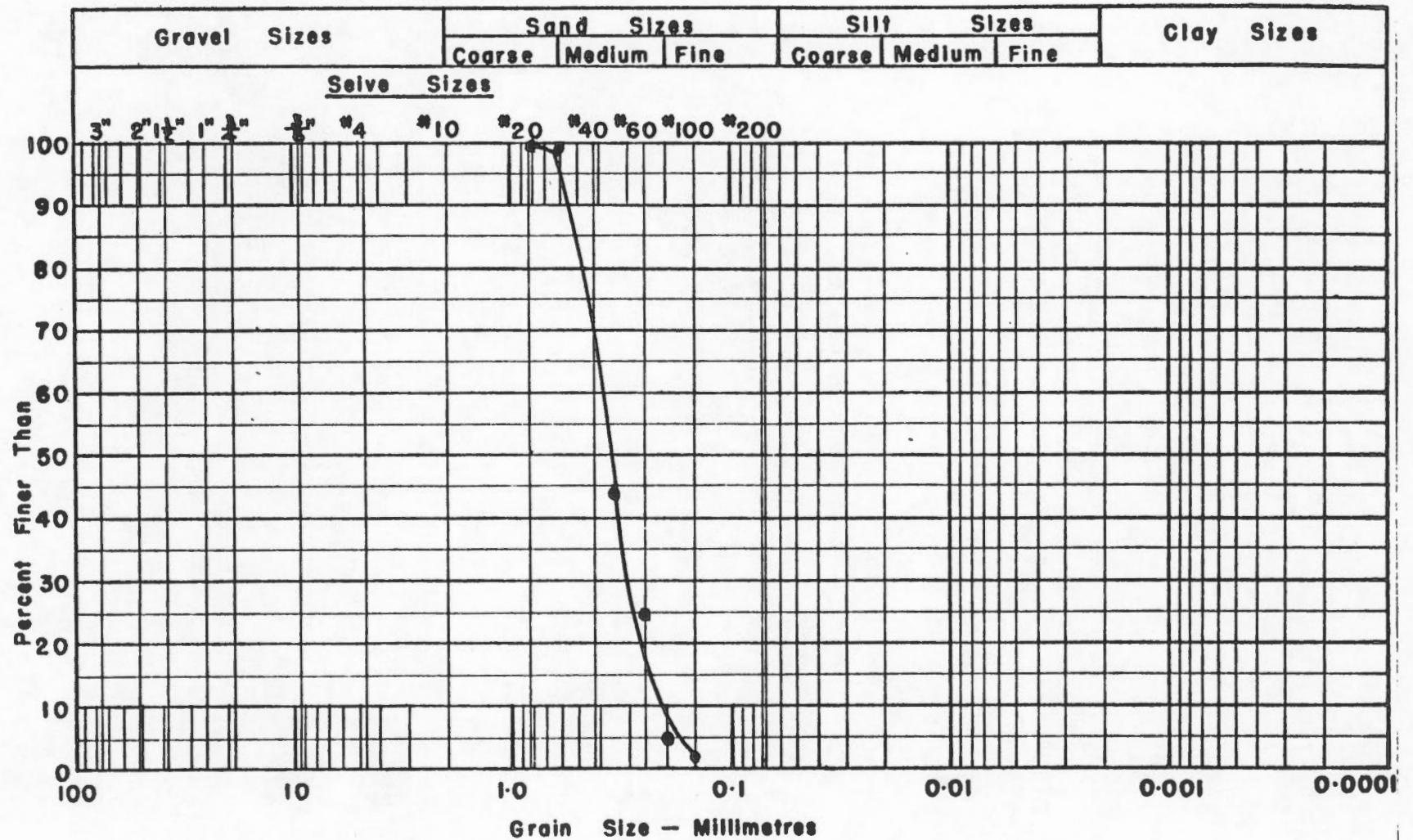


Figure 5 Grain size curve of test sand.

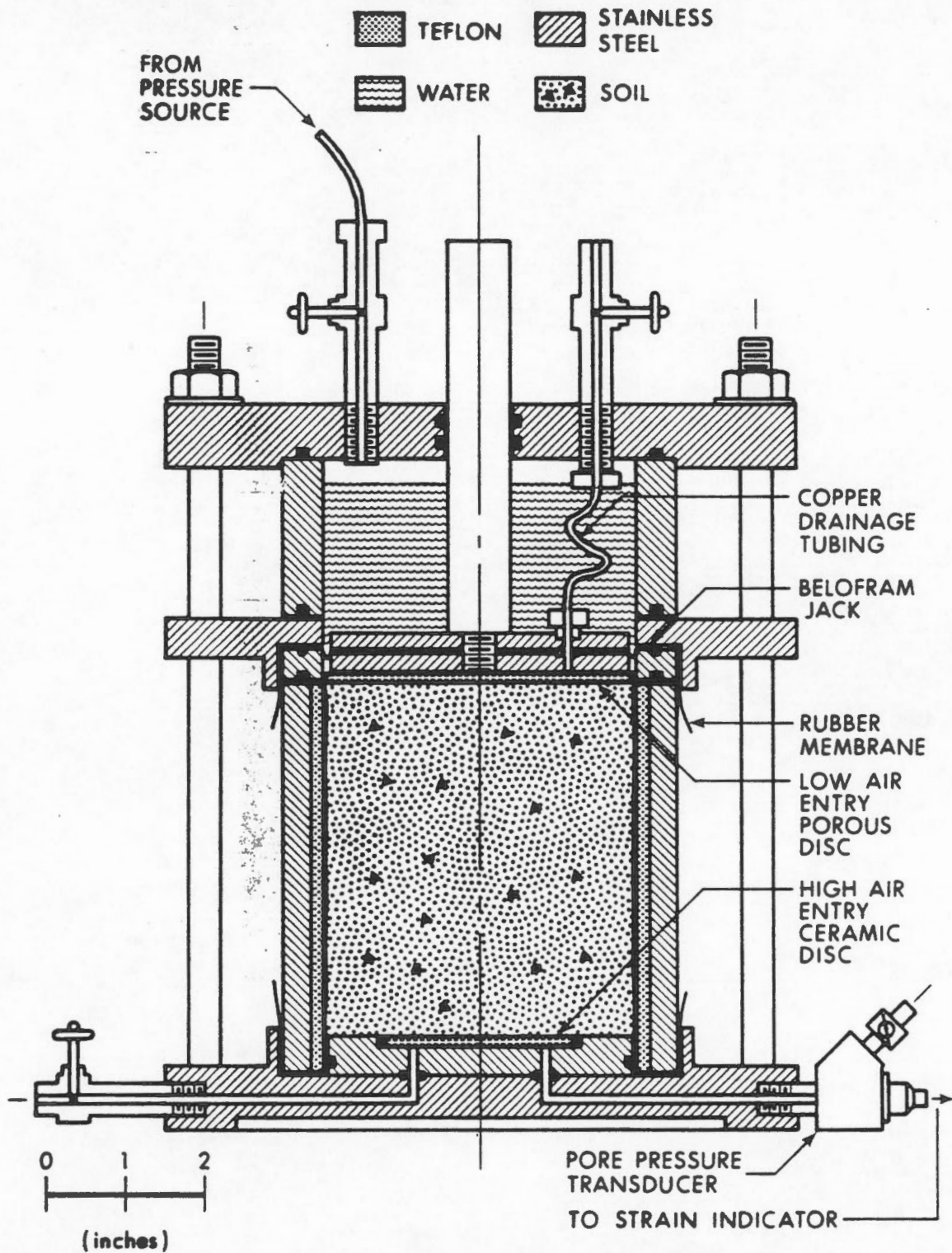


Figure 6 Modified Rowe consolidation cell.

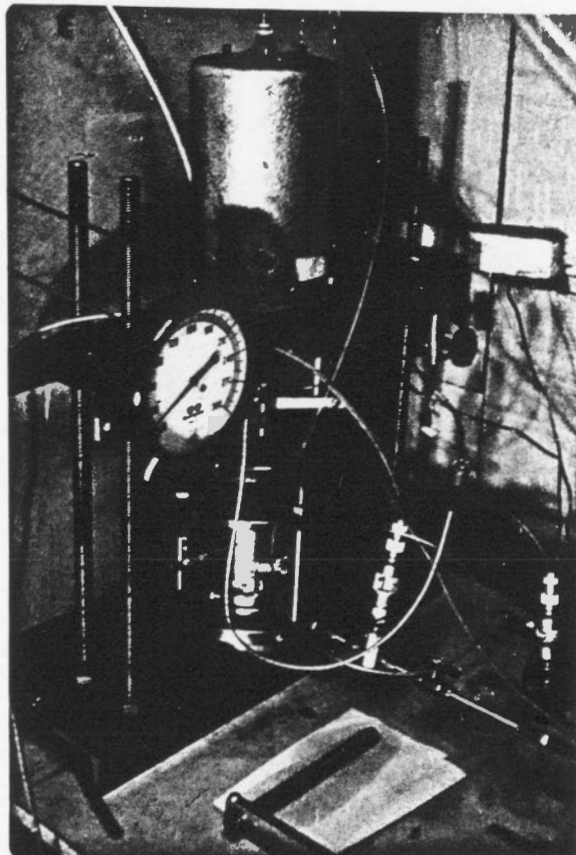


Figure 7 One dimensional volume change apparatus.

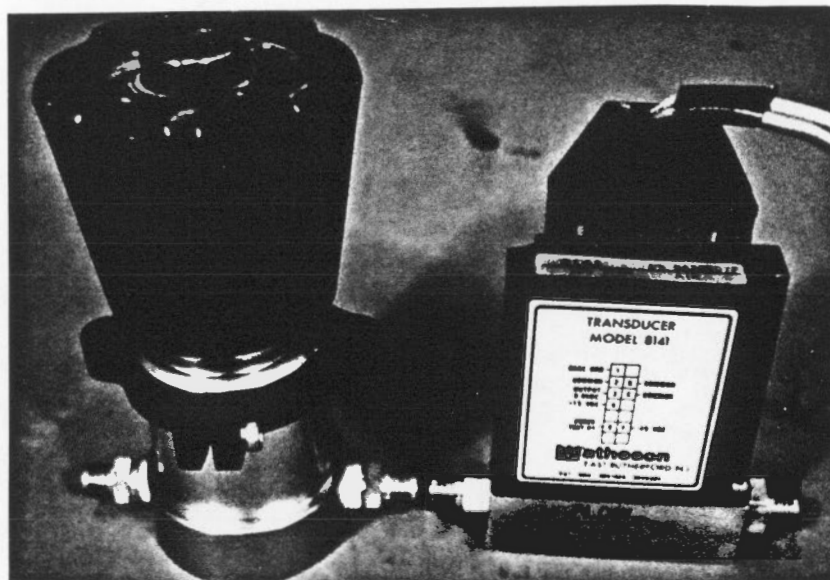


Figure 8 Flowmeter and backpressure regulator.

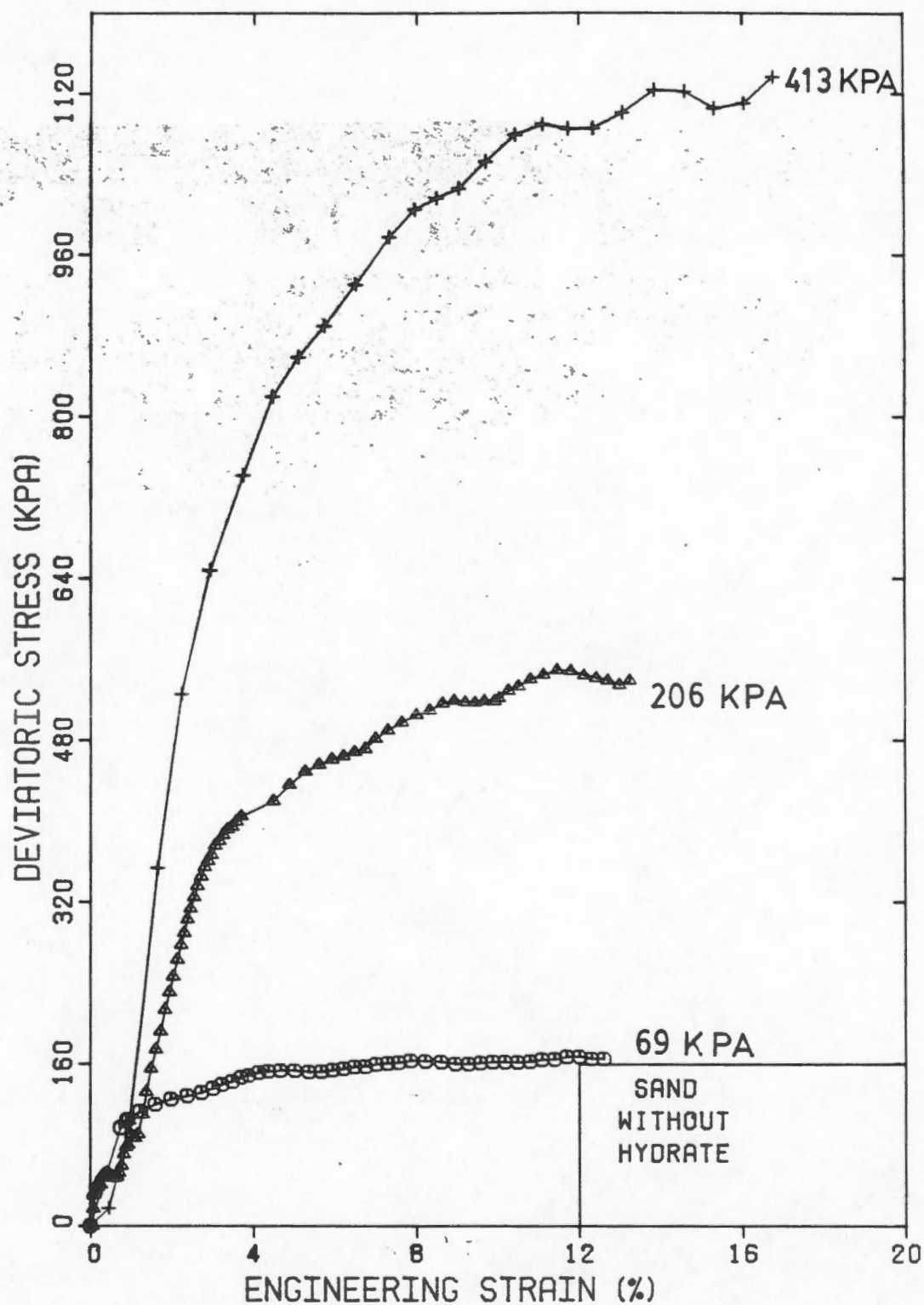


Figure 9 Stress-strain curve of sand without hydrate.

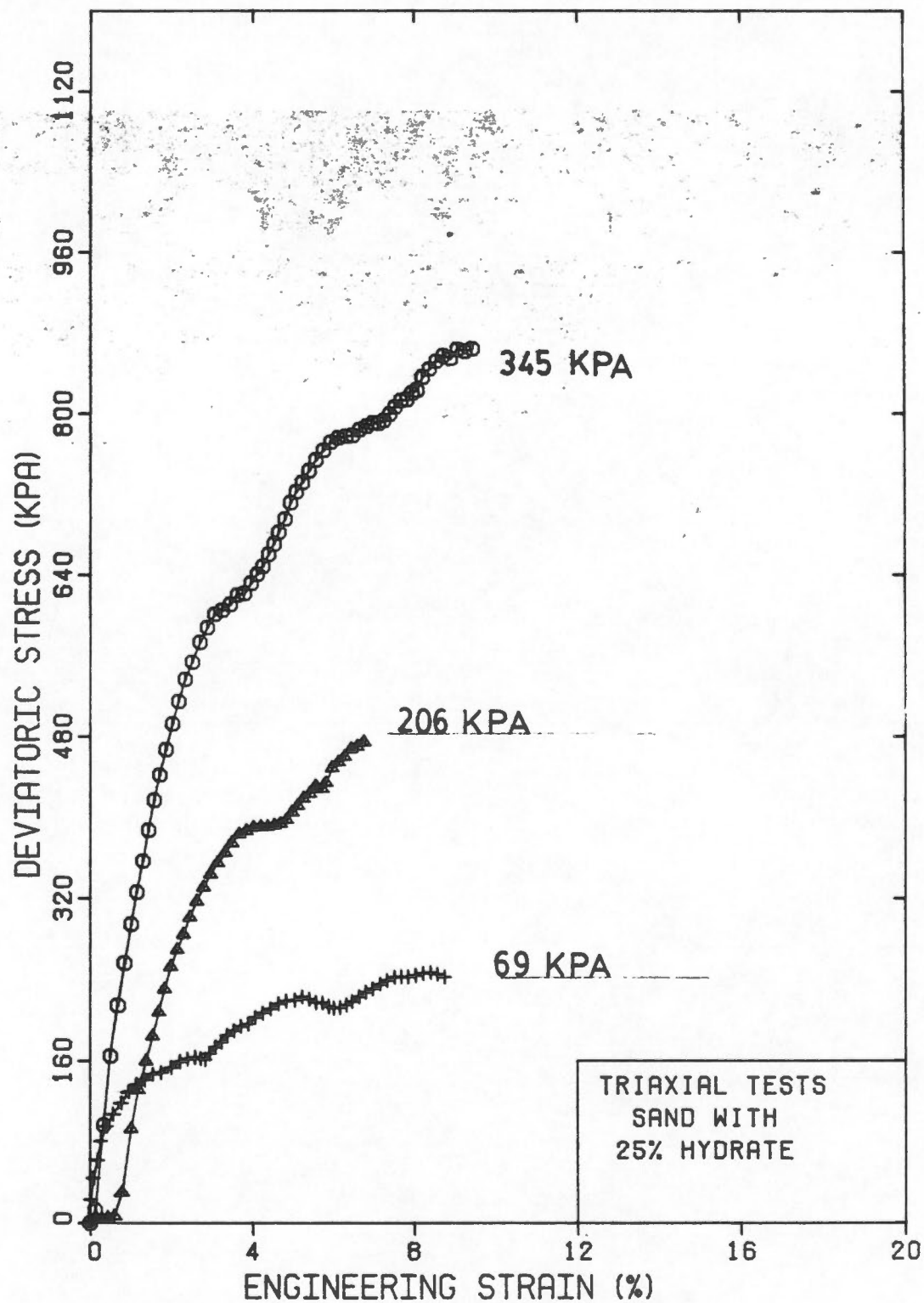


Figure 10 Stress-strain curve of sand 25% hydrate.

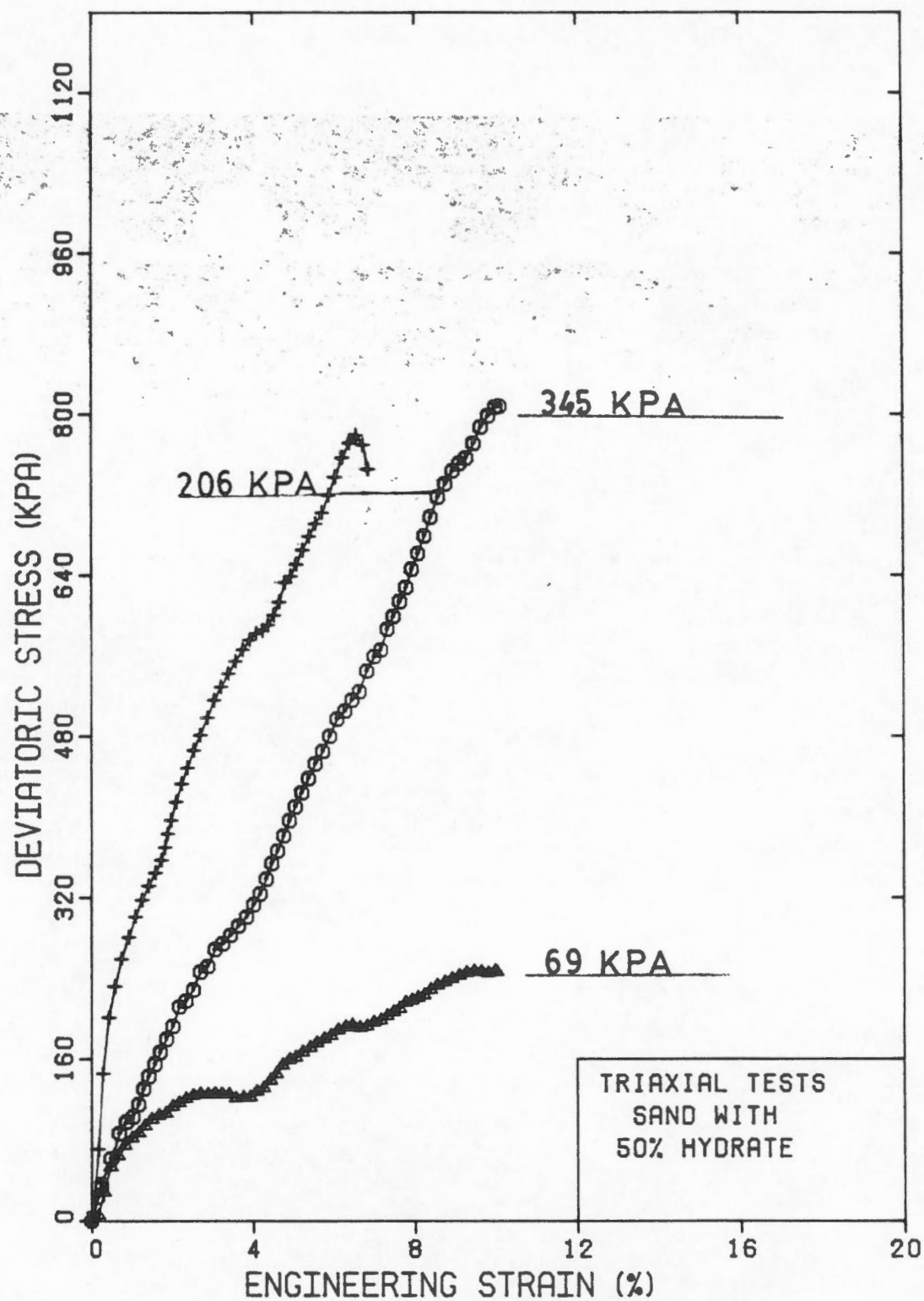


Figure 11 Stress-strain curve of sand 50% hydrate.

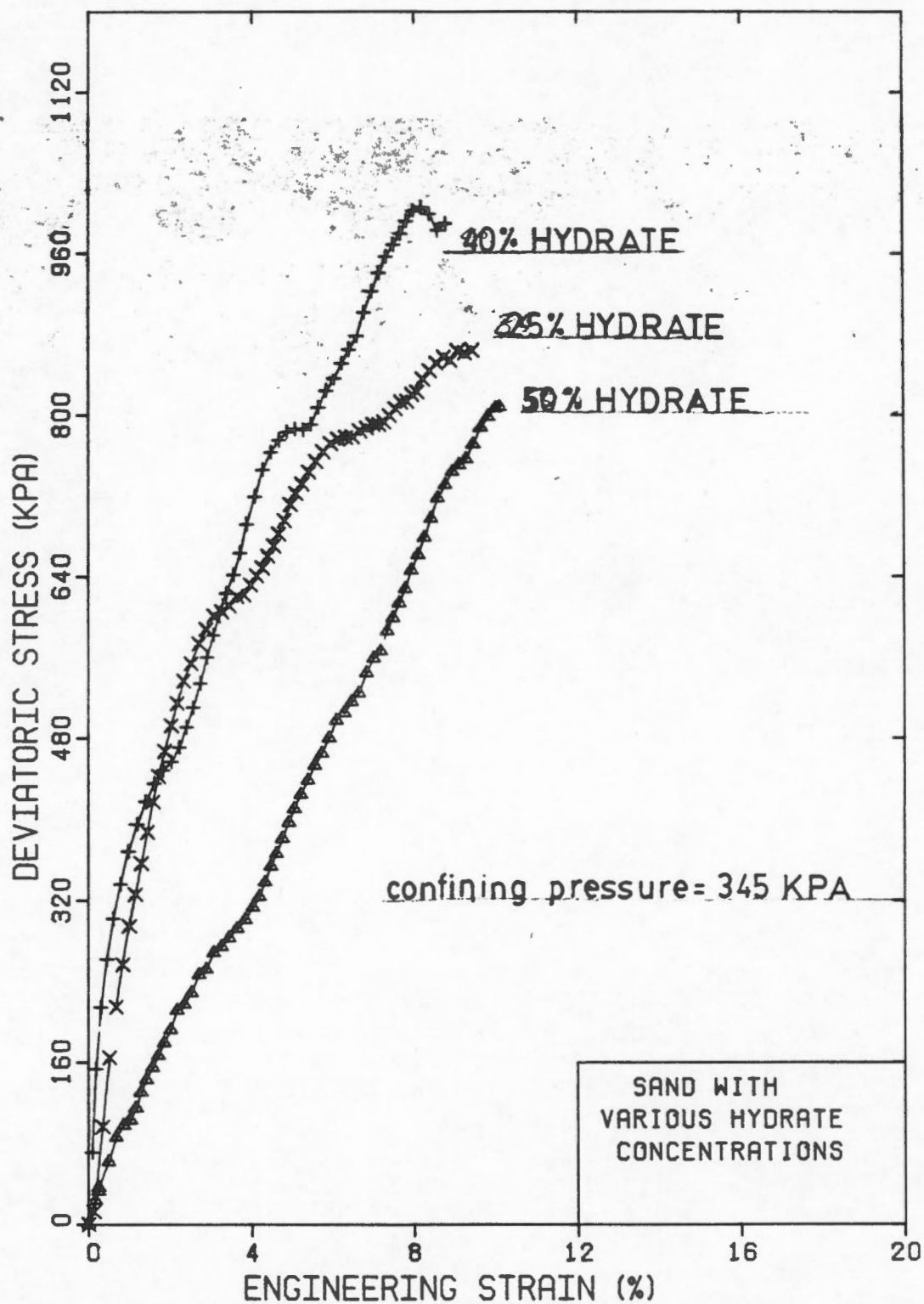


Figure 12 Stress-strain curve of sand with various percentage of hydrate and a confining pressure of 345 kPa.

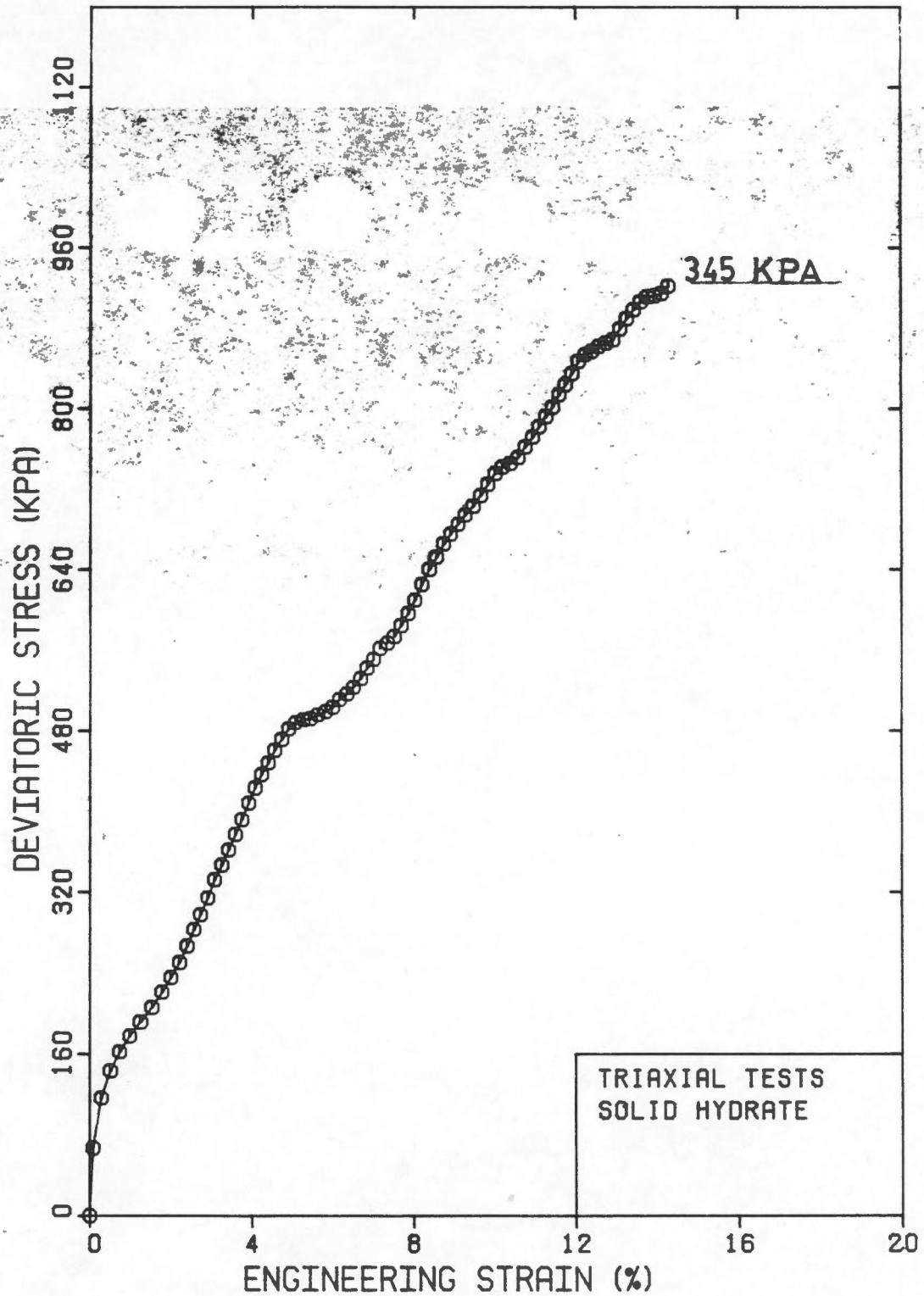


Figure 13 Stress-strain curve of solid hydrate sample.

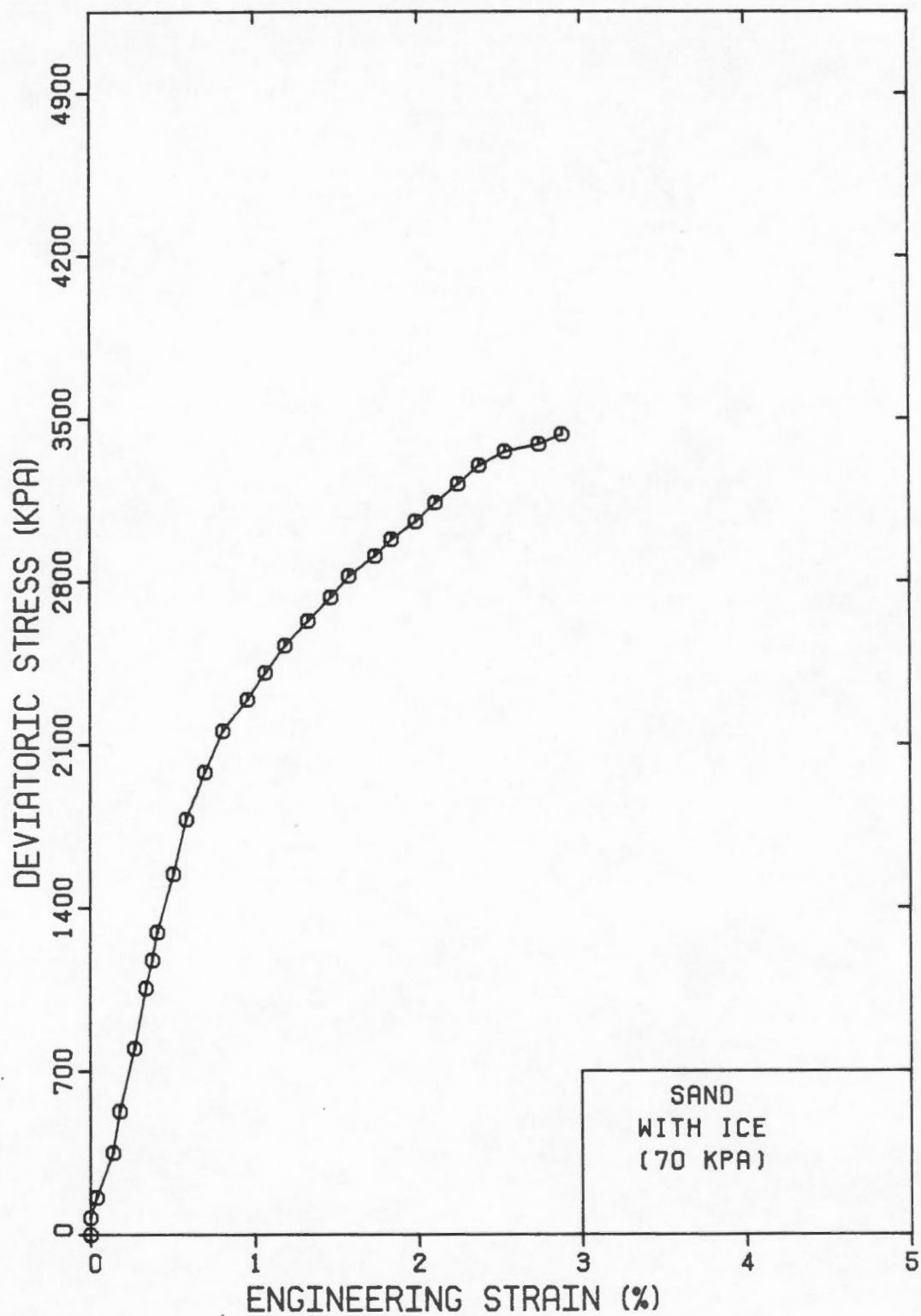


Figure 14 Stress-strain curve of sand at -6.0°C .

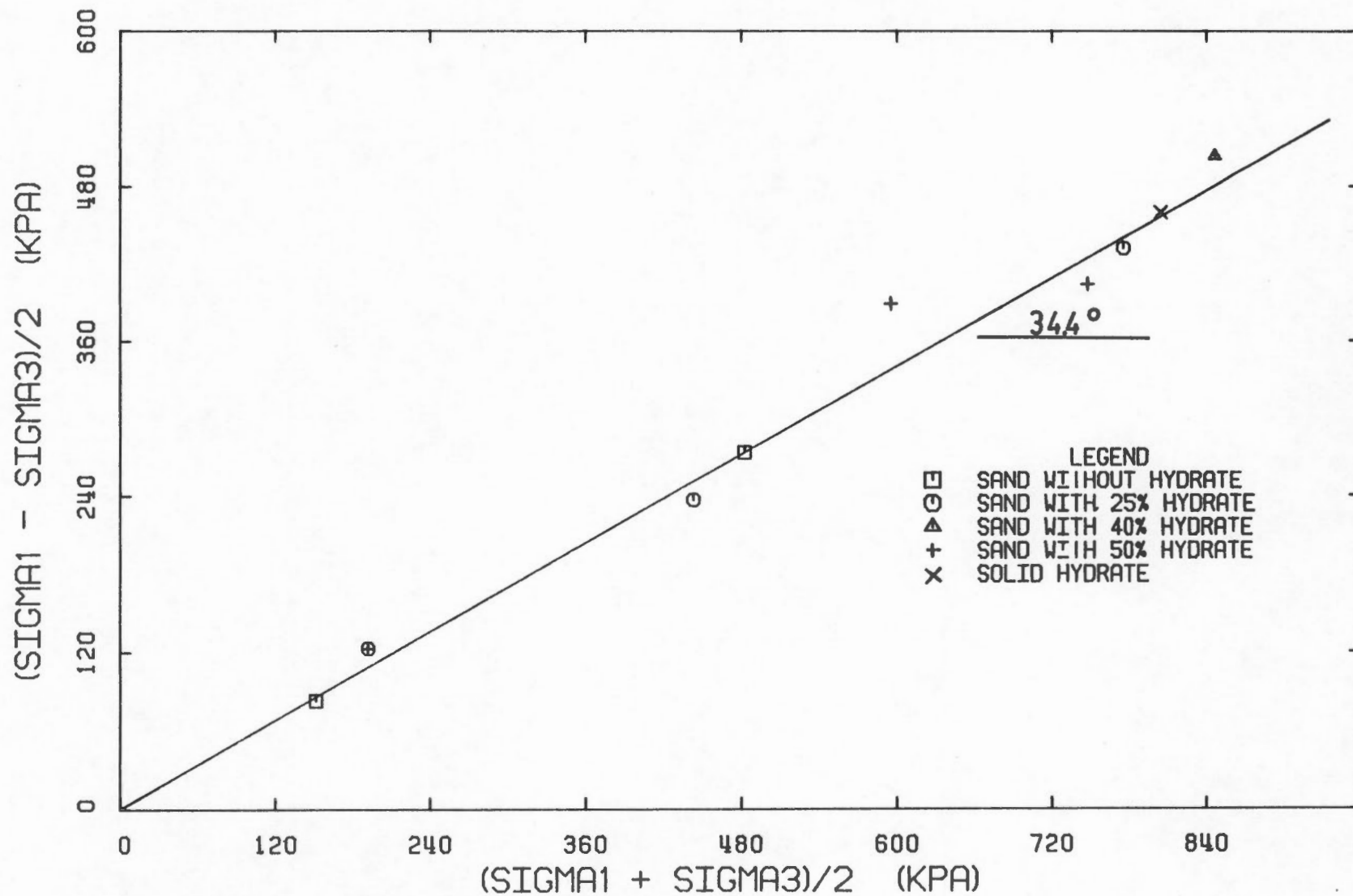


Figure 15 Summary P-Q plot of all test results.

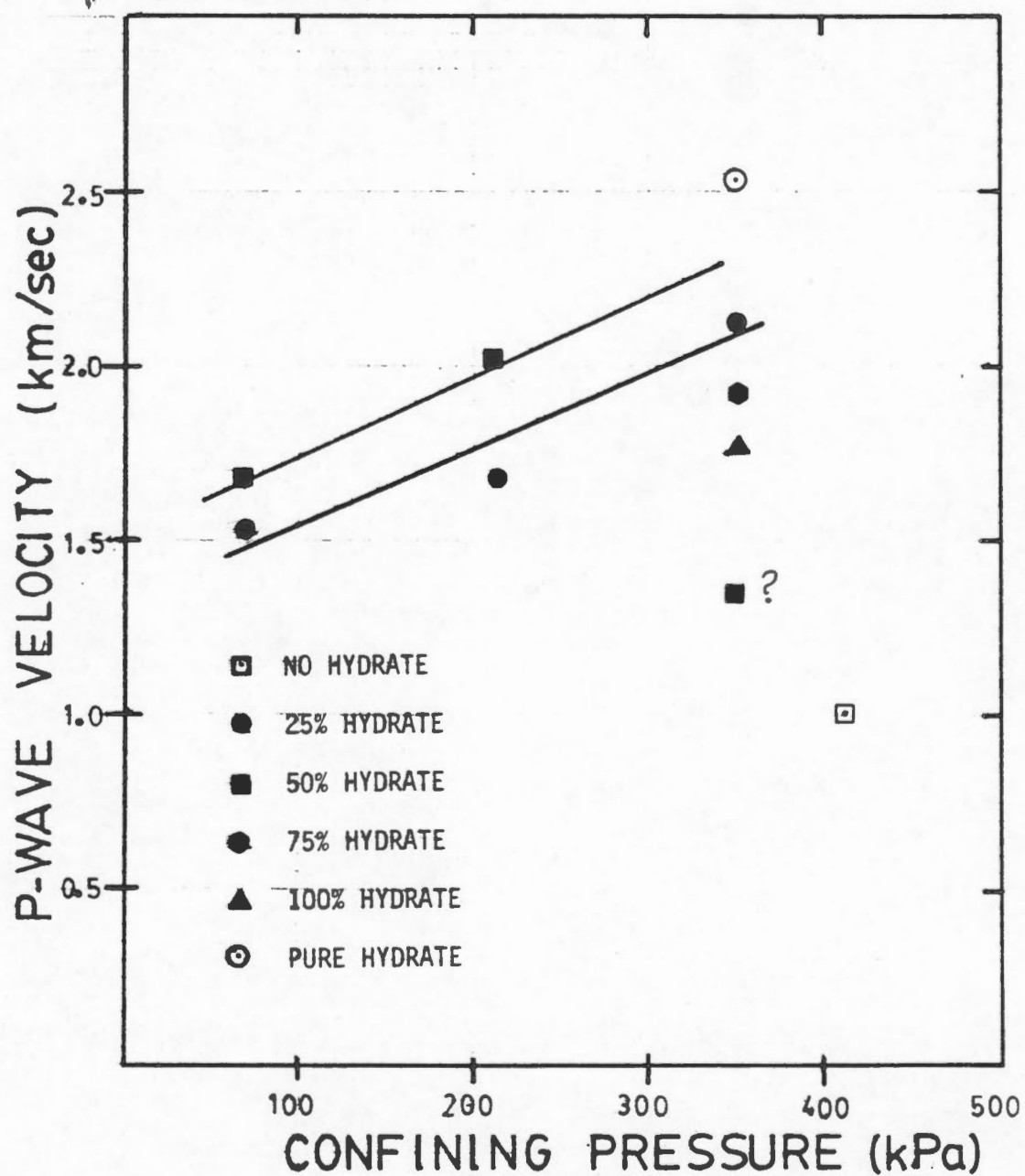


Figure 16 Compressional wave velocity versus confining pressure of samples at various % hydrate and +2.0°C.



Figure 17 One dimensional volume change flow data.

SHEAR STRESS (kPa)

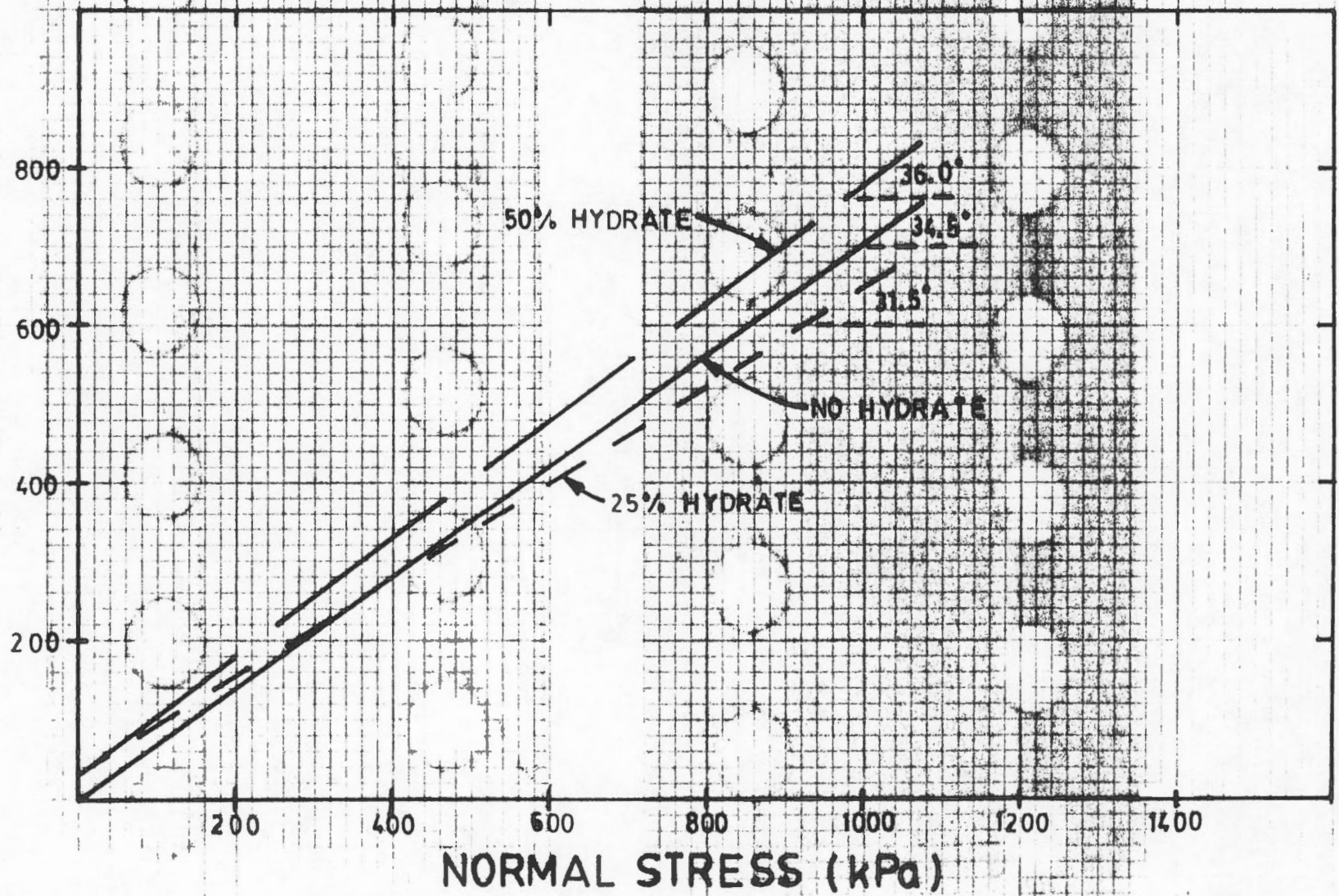


Figure 18 Mohr plot of sand and hydrate saturated sand.

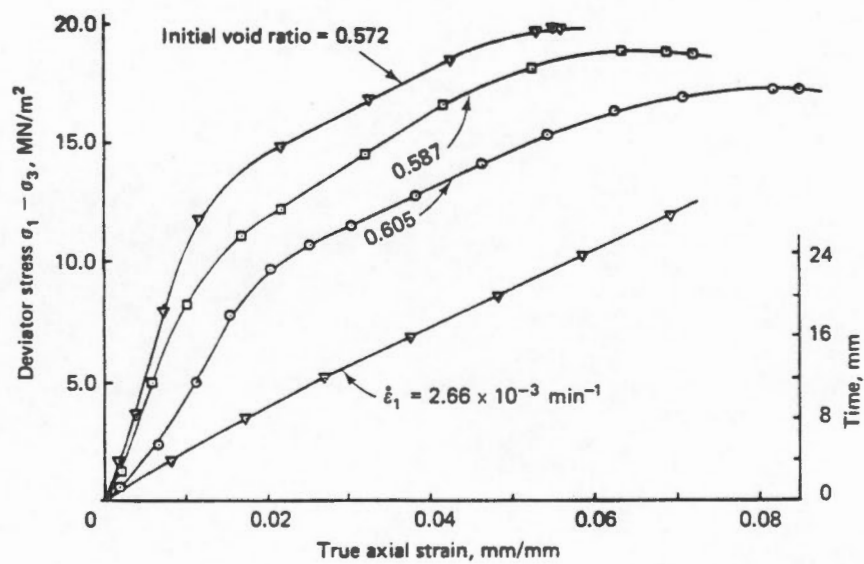


Figure 19 Influence of void ratio on the stress-strain behaviour for Ottawa Sand. (After Alkire and Andersland, 1973)

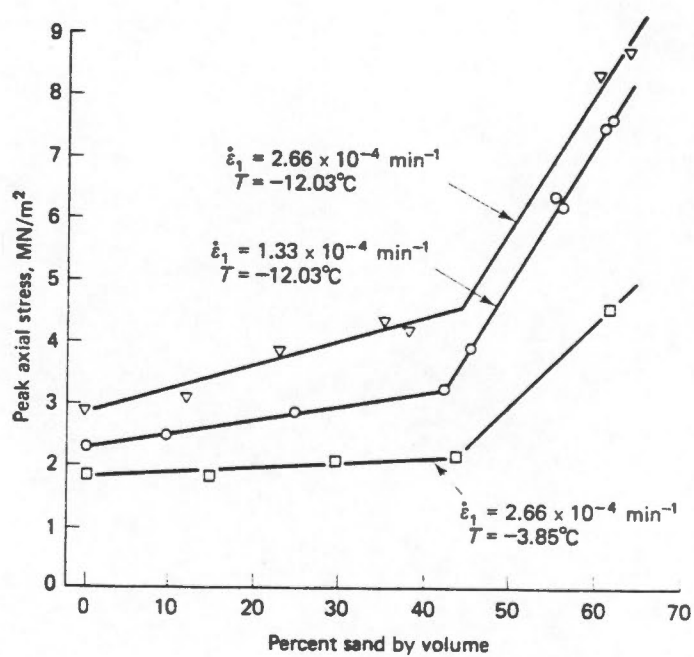


Figure 20 Volume concentration of Ottawa sand and peak strength. (After Goughnour and Andersland, 1968.)

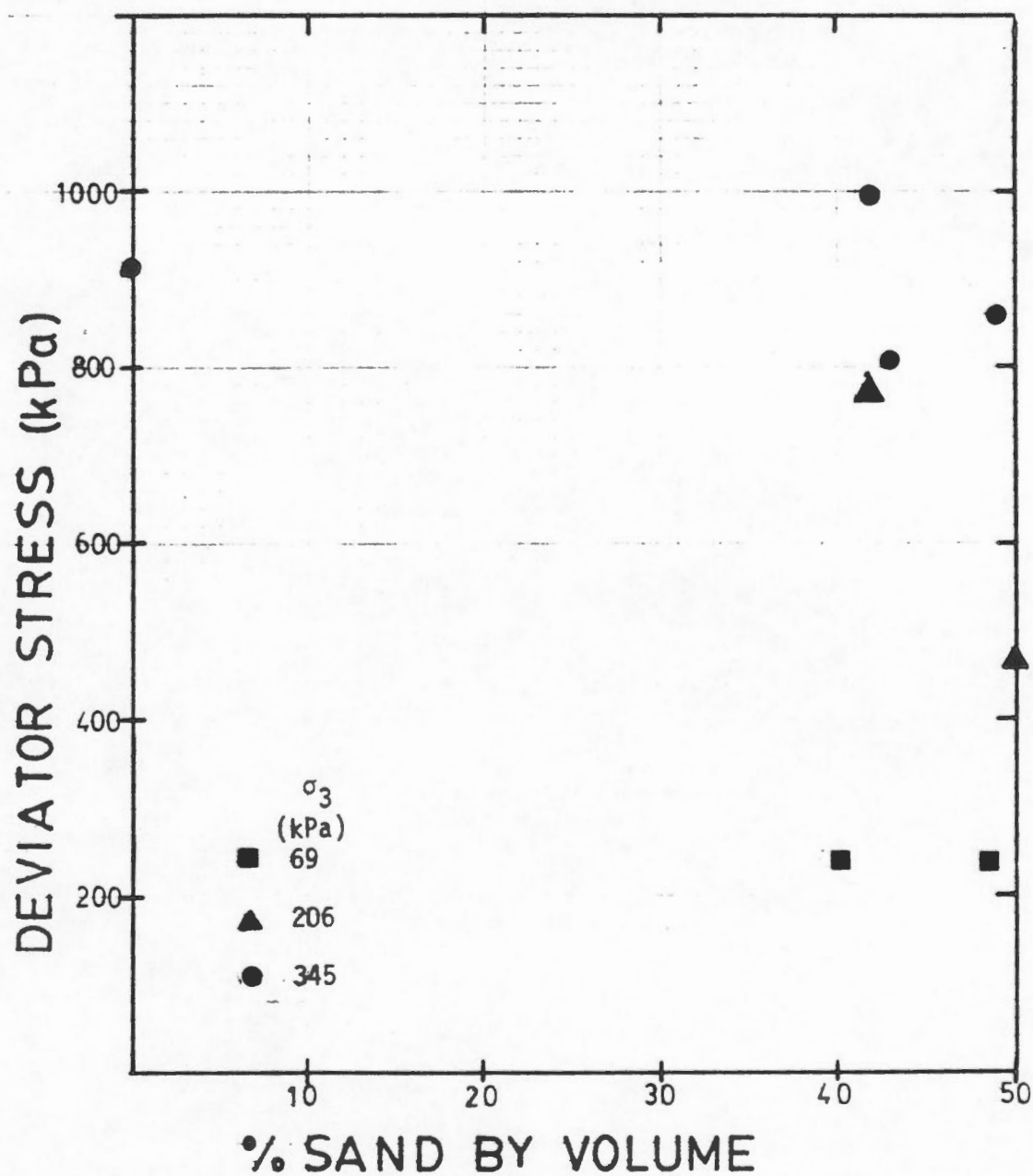


Figure 21 Volume concentration of hydrate saturated sand and peak deviator stress.