N72-13824
NASA CR 121043

GEOTECHNICAL ENGINEERING

LUNAR SURFACE ENGINEERING PROPERTIES EXPERIMENT DEFINITION

SUMMARY TECHNICAL REPORT

CASE FILE COPY

by

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PREPARED FOR GEORGE C. MARSHALL SPACE FLIGHT CENTER
HUNTSVILLE, ALABAMA, UNDER NASA CONTRACT NAS 8-21432

JULY 1971

SPACE SCIENCES LABORATORY

UNIVERSITY OF CALIFORNIA · BERKELEY

Space Sciences Laboratory
University of California
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Control Number DCN 1-X-80-00058 S1 (IF)

July 1971

Space Sciences Laboratory Series 11 Issue 52

This report was prepared by the University of California, Berkeley, under Contract Number NAS 8-21432, Lunar Surface Engineering Properties Experiment Definition, for the George C. Marshall Space Flight Center of the National Aeronautics and Space Administration. This work was administered under the technical direction of the Space Sciences Laboratory of the George C. Marshall Space Flight Center.

PREFACE

This report presents the results of studies conducted during the period July 19, 1969 — July 19, 1970, under NASA Research Contract NAS 8-21432, "Lunar Surface Engineering Properties Experiment Definition." This study was sponsored by the Lunar Exploration Office, NASA Headquarters, and was under the technical cognizance of Dr. N. C. Costes, Space Science Laboratory, George C. Marshall Space Flight Center.

The report reflects the combined effort of five faculty investigators, a research engineer, a project manager, and eight graduate research assistants, representing several engineering and scientific disciplines pertinent to the study of lunar surface material properties. James K. Mitchell, Professor of Civil Engineering, served as Principal Investigator and was responsible for those phases of the work concerned with problems relating to the engineering properties of lunar soils and lunar soil mechanics. Co-investigators were William N. Houston, Assistant Professor of Civil Engineering, who was concerned with problems relating to the engineering properties of lunar soils; Richard E. Goodman, Associate Professor of Geological Engineering, who was concerned with the engineering geology and rock mechanics aspects of the lunar surface; Paul A. Witherspoon, Professor of Geological Engineering, who was concerned with fluid conductivity of lunar surface materials in general; Franklin C. Hurlbut, Professor of Aeronautical Science, who was concerned with experimental studies on fluid conductivity of lunar surface materials; and D. Roger Willis, Associate Professor of Aeronautical Science, who conducted theoretical studies on fluid conductivity of lunar surface materials. Dr. Karel Drozd, Assistant Research Engineer, performed laboratory tests and analyses pertinent to the development of a borehole jack for determination of the in situ characteristics of lunar soils and rocks; he also helped in the design of the borehole jack. H. Turan Durgunoglu, H. John Hovland, Laith I. Namiq, Parabaronen Raghuraman, James B. Thompson, Donald D. Treadwell, C. Robert Jih, Suphon Chirapuntu, and Tran K. Van served as Graduate Research Assistants and carried out many of the studies leading to the results presented in this report. Ted S. Vinson, Research Engineer, served as project manager until May 1970, and contributed to studies concerned with lunar soil stabilization. H. John Hovland served as project manager after May 1970, and contributed to studies concerned with soil property evaluation from lunar boulder tracks.

Ultimate objectives of this project were:

1) Assessment of lunar soil and rock property data using information obtained from Lunar Orbiter, Surveyor, and Apollo missions.

2) Recommendation of both simple and sophisticated in situ testing techniques that would allow determination of engineering properties of lunar surface materials.

3) Determination of the influence of variations in lunar surface conditions on the performance parameters of a lunar roving vehicle.

4) Development of simple means for determining the fluid conductivity properties of lunar surface materials.

5) Development of stabilization techniques for use in loose, unconsolidated lunar surface materials to improve the performance of such materials in lunar engineering application.

The scope of specific studies conducted in satisfaction of these objectives is indicated by the following list of contents from the Detailed Final Report which is presented in four volumes. The names of the investigators associated with each phase of the work are indicated.

VOLUME I

MECHANICS, PROPERTIES, AND STABILIZATION OF LUNAR SOILS

VOLUME II

MECHANICS OF ROLLING SPHERE-SOIL SLOPE INTERACTION
H. J. Hovland and J. K. Mitchell

VOLUME III

BOREHOLE PROBES

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FLUID CONDUCTIVITY OF LUNAR SURFACE MATERIALS

SUMMARY TECHNICAL REPORT

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SUMMARY TECHNICAL REPORT

Lunar Surface Engineering Properties Experiment Definition

Lunar Soil Simulant Studies

by

W. N. Houston, L. I. Namiq, J. K. Mitchell, and D. D. Treadwell

SUMMARY AND CONCLUSIONS

The gradation of the Lunar Soil Simulant used in previous studies (LSS No. 1), Houston, Namiq, and Mitchell (1970), was modified to more closely match the gradation of samples returned from Apollo 11 and 12 missions by decreasing the percentage of material coarser than 1 mm shown in Figure 1. The penetration resistance characteristics of the fraction finer than 1 mm of Lunar Soil Simulants Nos. 1 and 2 match those of the corresponding fraction of Apollo 11 soil very well, as shown in Figure 2.

The behavior of the Lunar Soil Simulant was investigated, and the following conclusions can be made:

1. Lunar Soil Simulant No. 2 appears to be a good match for the actual lunar soil in terms of gradation, penetration resistance, and other physical properties.

2. The conclusion reported in the Final Report of January 1970 (Mitchell and Houston, Vol. I) regarding the sensitivity of lunar soil properties to void ratio is reinforced by studies on LSS No. 2. These studies indicate that most soil properties of interest can be predicted from knowledge of the void ratio.

3. Strength, stress-strain, and one-dimensional compression parameters of the lunar soil simulant have all been related to void ratio in both equation and graphic form. The idealized

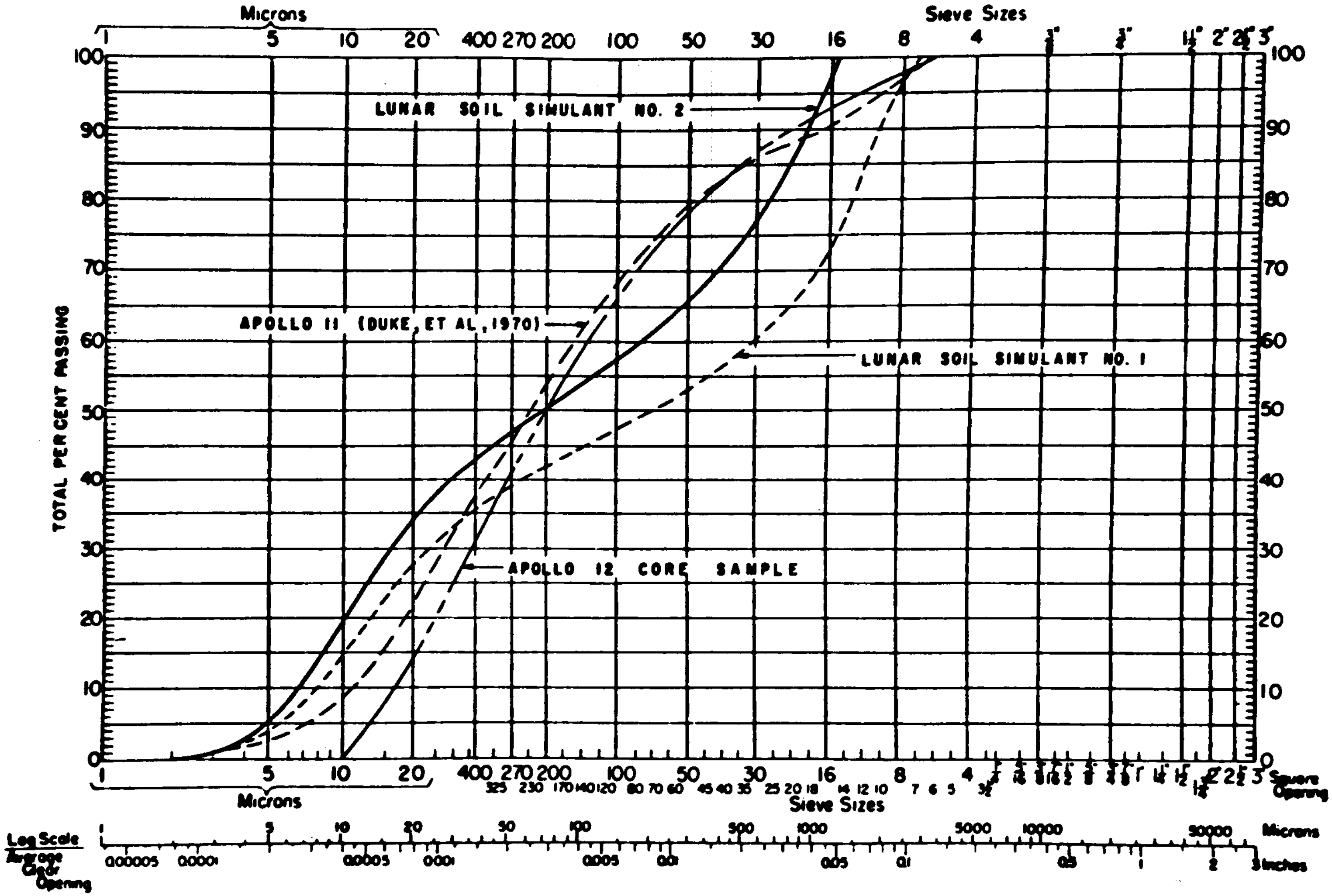

Fig. 1. Gradation curves for Lunar Soil Simulants Nos. 1 and 2 and Apollo 11 and 12 materials.

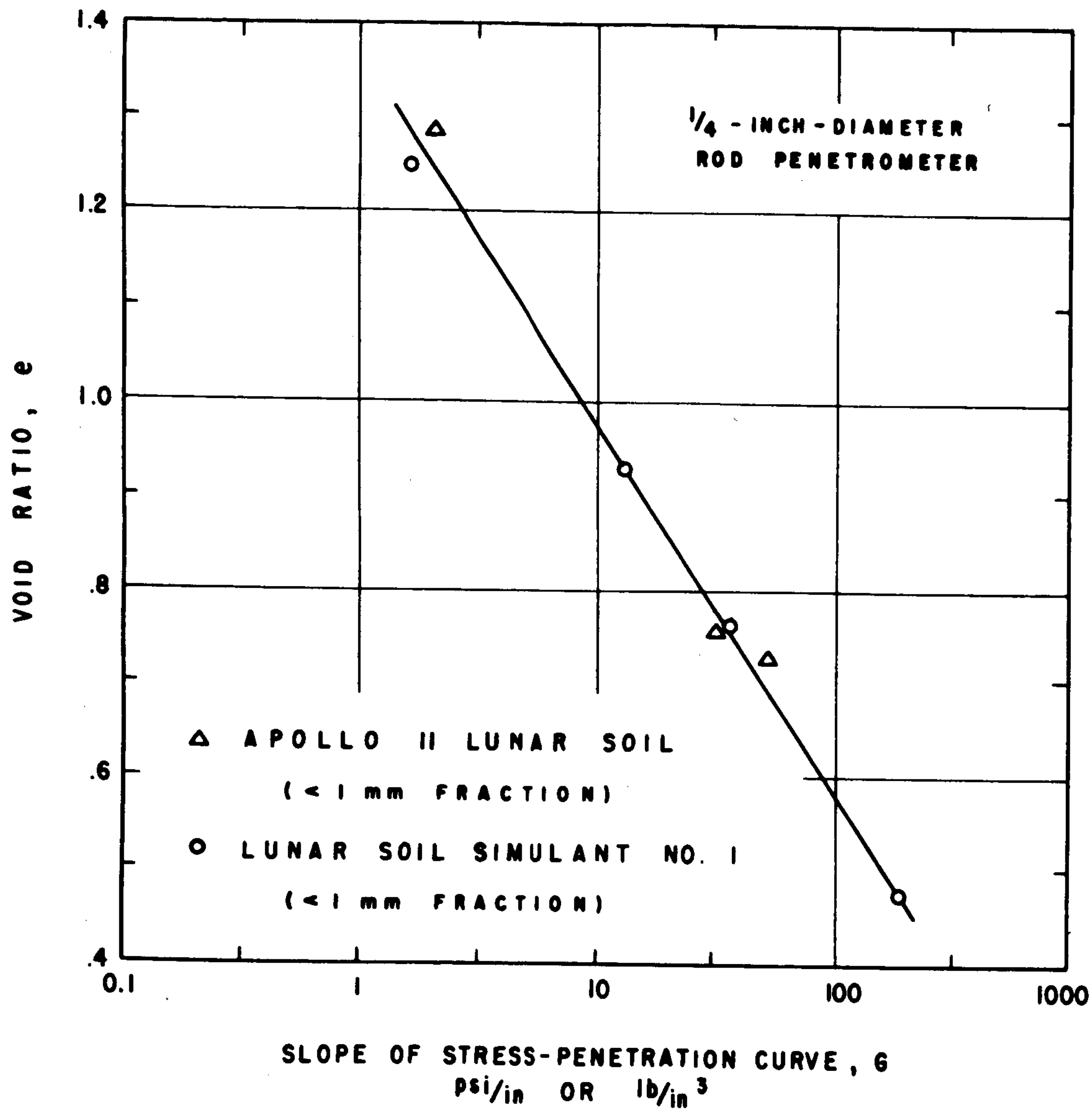

Fig. 2. Relationship between G and void ratio for Apollo 11 lunar soil, Costes et al. (1970), and for Lunar Soil Simulant No. 1.

compression curves obtained are shown in Figure 3. One-dimensional compression parameters have been used to estimate density profiles for both terrestrial gravity and lunar gravity conditions. These profiles show that the increase in density with depth should be less pronounced for the lunar surface than for the same soil on earth.

4. Cohesion was measured. It was found that the Lunar Soil Simulant at a water content of about 1.9 to 2.0 per cent exhibited cohesion values in the range 0.01 to 0.1 psi. This range is similar to that observed for lunar soil.

5. One-dimensional compression parameters and plane strain stress-strain parameters were used in a stress path method of analysis to compute the soil deformations under a 4-inch by 20-inch plate acted on by a 1-psi vertical stress for several initial void ratios. The computed values were compared with the measured plate load sinkage and the agreement was fairly good. The stress path computations were repeated for reduced gravity, and gravity reduction factors were obtained. These factors were used to relate footprint depth to void ratio as shown in Figure 4. Estimates of footprint depths from Apollo 11 and 12 photos gave a range of 0.1 to 0.5 inch for most values, with an average value of about 0.25 inch. This footprint depth corresponds to an estimate of e_{ave} for the top 15 cm of 0.85 on the lunar surface. This corresponds to an in situ density of about 1.7 gm/cm^3, for $G_s = 3.1$.

6. Plate load tests (1-inch to 4-inch wide plates) were conducted on the Lunar Soil Simulant, and the results indicated that no

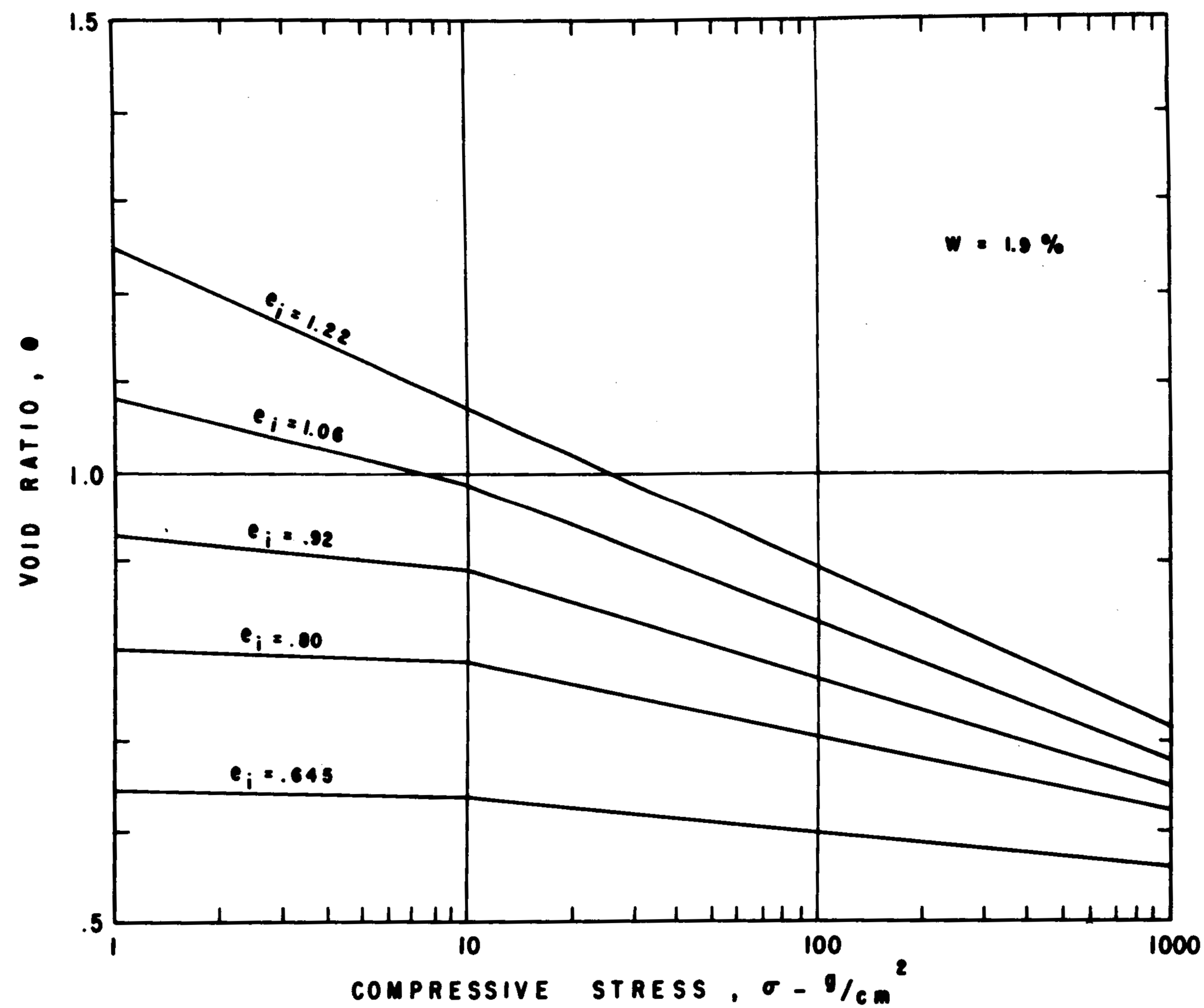

Fig. 3. One-dimensional compression curves for Lunar Soil Simulant No. 2 at 1.9% water content.

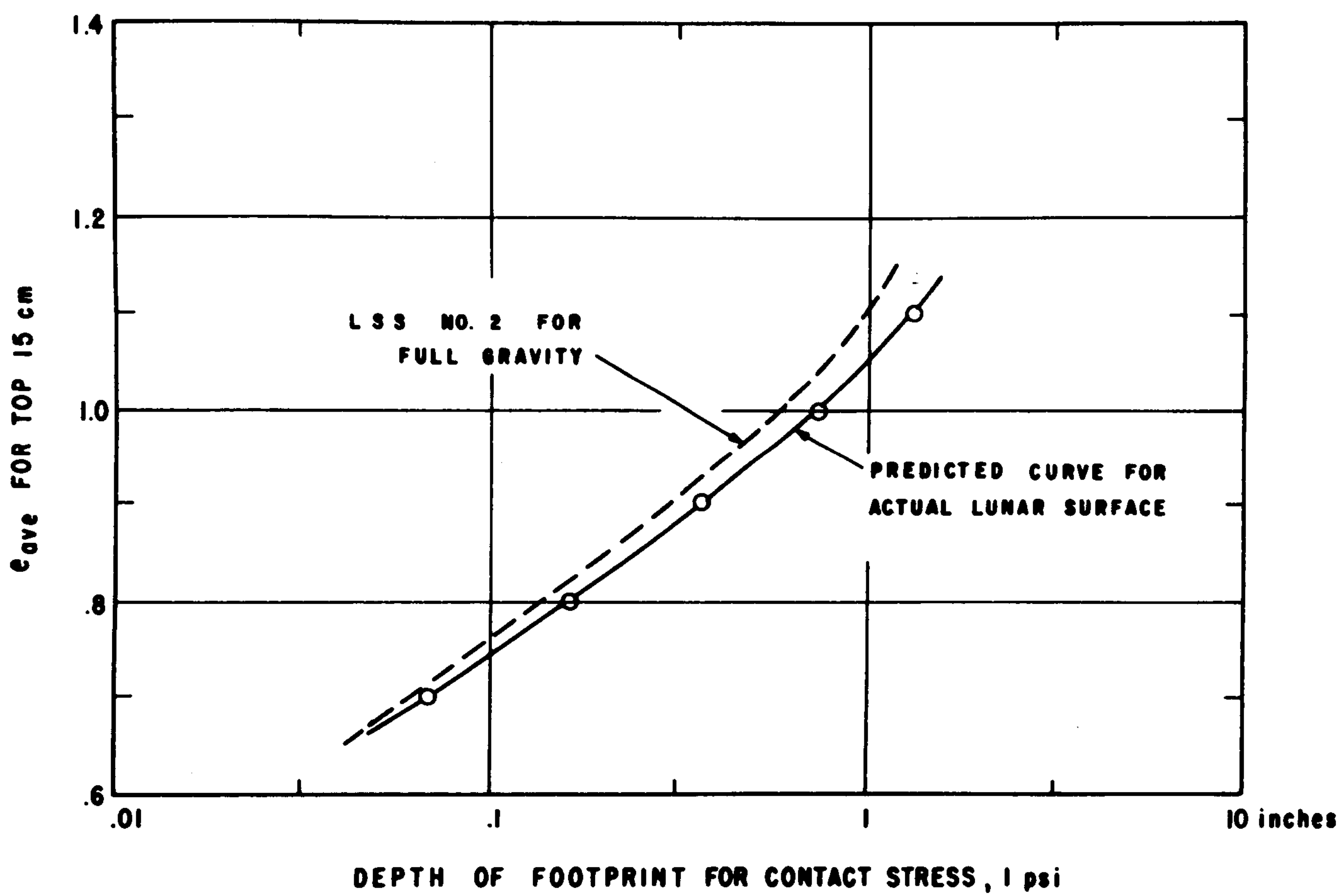

Fig. 4. Predicted variation of footprint depth with void ratio for actual lunar surface.

general shear failure occurred, except perhaps in the case of loading by the 1-inch plate on the very dense soil. However, the data showed that the sinkages were quite large, ranging up to one and two plate-widths.

7. A bearing capacity equation was used to estimate the G value for the Lunar Soil Simulant under full gravity and yielded very good agreement with values measured directly with a penetrometer when local shear strength parameters were used. A similar set of computations for reduced gravity led to the predicted relationship between G and void ratio for the lunar surface shown in Figure 5. Figure 5 indicates that G may range from 2.5 psi/inch (for the estimated $e_{ave} = 0.85$ from the boot imprint analysis) to 5.4 psi/inch (for the estimated $e_{ave} = 0.73$ from Apollo 12 core tube density analysis; Scott et al., 1971).

RECOMMENDATIONS

1. Good measurements of in-place density on the lunar surface soil are needed. The core tube sampler should be modified by greatly reducing the area ratio in an effort to obtain higher sample recovery and samples with less disturbance. Other types of in-place density tests should also be considered.
2. Measurements of G value by the astronauts during Apollo missions are needed as soon as possible. These penetration resistance measurements should be made using a penetrometer with a 30-degree cone, 0.5-square-inch base area, and 5/8-inch-diameter shaft with a load and penetration measurement device.
3. Plate load tests should be performed on Apollo missions as soon as possible. The studies reported herein indicate that useful information pertaining to void ratio and other mechanical

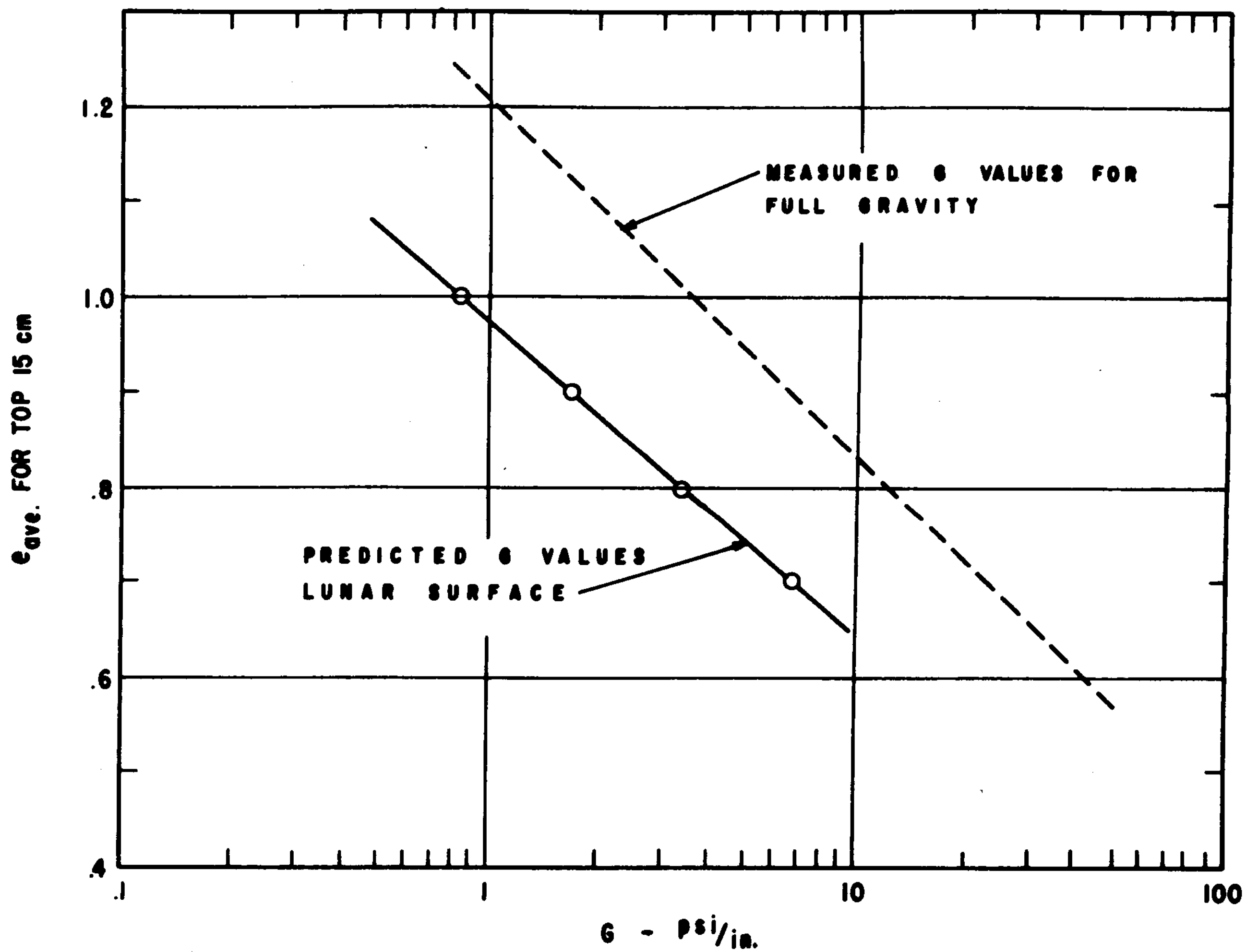

Fig. 5. Predicted variation of G value with void ratio for actual lunar surface.

properties can be derived from plate load tests. The plate load tests could be performed by attaching a plate to the penetrometer extension handle, or by having the astronaut lower a large (4-inch) plate to the surface and step on it with his full weight. Photos should be taken before and after loading.

4. Analyses of the plate load test results should be continued using both the stress path method and the finite element method.

5. Values of G should be determined for a good Lunar Soil Simulant under conditions of reduced gravity. Although the predictions obtained in this study using a bearing capacity equation appear to be reliable, a high degree of certainty can only be obtained by making measurements in a 1/6 g aircraft simulation.

6. Additional strength and stress-strain tests should be performed with confining pressures as low as 0.01 kg/cm^2. Although the extrapolation to lower confining pressures used may well be reliable, the extent of extrapolation necessary was quite large. Very small specimens will probably be required because the weight of specimens of conventional size produces significant internal stress.

Determination of In Situ Soil Properties Utilizing an Impact Penetrometer

by

J. B. Thompson and J. K. Mitchell

SUMMARY AND CONCLUSIONS

The feasibility of evaluating soil properties from data obtained from the impact of a slender penetrometer with a soil deposit was investigated. The primary purpose was to determine which soil properties can be evaluated from the penetrometer output and the probable accuracy of the results. This study considered the potential of the impact penetration test and existing theoretical and empirical approaches for relating the dependent and independent variables of the problem. The investigation led to the following conclusions:

1. The use of the impact penetration test as a technique for determining in situ soil properties is promising. Indications are that impact penetration tests can yield results of approximately the same accuracy as other common techniques for determining in situ soil properties. At the same time, the impact penetration test possesses the following advantages for evaluating soil deposits on an extraterrestrial body:
   - (a) Provisions for soft landing would not be required, and
   - (b) The penetrometer along with any necessary instrumentation would likely compose a relatively small, inexpensive package, economically allowing extensive deployment.
2. Inadequacies in existing experimental test data inhibit:
   - (a) Development of a proper understanding of the deformation patterns produced during impact penetration,

(b) Evaluation of existing theoretical and empirical analytical expressions,

(c) Development of new theoretical and empirical analytical expressions, and

(d) Extrapolation of terrestrially derived expressions to the linear environment. These inadequacies in test data are due primarily to the following factors:

(a) Each experimental program utilized penetrometers of different dimensions and frequently different shapes,

(b) Tests in which soil properties were well controlled have usually been limited to very low impact velocities and in no study has the penetration at zero impact velocity been determined,

(c) In very few test programs were the soil properties varied over a sufficiently wide range,

(d) The influence of the air pressure at the soil surface has been studied only under limited conditions, and

(e) The influence of the gravitational field has not been studied.

RECOMMENDATIONS

It is recommended that an experimental test program be conducted. The experimental program designed to alleviate the above inadequacies will utilize:

1. A cone tipped right-circular cylinder penetrometer instrumented with a crystal accelerometer, and
2. A dry granular soil.

The independent variables to be studied include impact velocity, air pressure at the soil surface, soil void ratio, specific gravity of soil solids, grain size and shape parameters, and soil particle mineralogy. The fabrication of the equipment required to conduct this experimental program is now in progress. After meaningful experimental data have been collected and the fundamental behavior of the penetrometer better understood, analytical investigations should be further pursued.

Lunar Soil Stabilization Using Urethane Foamed Plastics

by
T. S. Vinson, T. Durgunoglu, and J. K. Mitchell

SUMMARY AND CONCLUSIONS

It is believed that the use of chemical stabilization agents can be advantageous for increasing soil bearing capacity and for obtaining undisturbed soil samples.

The most desirable stabilizer for lunar soils will be one that stabilizes the greatest volume of soil per unit weight of stabilizer transported to the moon. Foamed plastics have been investigated for lunar soil stabilization applications because they offer very low density systems. Emphasis thus far has been primarily on soil grouting; i.e., the stabilization of a soil mass by injection of a liquid chemical system. Limited feasibility studies have also been made on lunar soil stabilization by (1) pouring or spraying urethane foamed systems on soil deposits, and (2) mixing urethane foamed systems with soil deposits; i.e., admixture stabilization.

The research program during the past year has involved:

1. Development and use of apparatus to investigate the influence of the lack of atmosphere on the urethane foaming process.
2. Stabilization of soil masses by injection grouting in vacuo.
3. Feasibility study of admixture stabilization using urethane foamed plastic.

Our investigations lead to the following conclusions:

1. A suitable foamed plastic system for use in vacuo must:
    (a) Withstand the internal gas pressure in vacuo; i.e., the tensile strength of the foam bubble skin must be considerably stronger than required at atmospheric pressure.

(b) Form a polymer rapidly — a function primarily of the relative rate of reactivity of TDI with various constituents in the chemical system, and

(c) Not vaporize rapidly in the high vacuum.

2. Most of the urethane foam systems developed yielded unsatisfactory foams in vacuo, probably because of:

   (a) Poor mixing in the vacuum apparatus

   (b) Slow polymer formation, and

   (c) High-temperature during the reaction.

3. It was discovered that under vacuum conditions foam formation in soil was distinctly different from that in an open glass jar. Therefore, further attempts to increase the polymer formation ability or to reduce the heat of reaction for foams generated in the absence of soil were discontinued.

4. It was found that masses of No. 20 Monterey Sand could readily be stabilized in vacuo; however, injections into a Lunar Soil Simulant did not prove successful, because of the relatively fine-grained nature of the simulant.

Grouting of fragmental rock masses or coarse-grained soil masses using urethane foamed plastic in the lunar environment should be possible. Urethane systems have been developed that can cause such masses to have high, unconfined, compressive strengths. The degree of impermeabilization attained in these systems remains to be determined. While the effects of temperature on the foaming process have not been investigated specifically, it is felt that systems could be formulated, or the existing systems could be modified, to allow foam formation within a reasonable range of temperatures.

5. Cylinders of Lunar Soil Simulant stabilized by using urethane foamed plastic as an admixture had unconfined compressive strengths of 700, 4350, and 2800 psi for foam contents of 5, 10, and 15 per cent (by total dry weight of soil). These extremely encouraging results indicate that the use of urethane or other foamed plastics as admixture lunar soil stabilizing agents appears to be feasible and possibly represents a realistic approach for stabilization of lunar soils that are too fine-grained for treatment by injection.

RECOMMENDATIONS

It is recommended that research be continued on the following aspects of lunar soil stabilization:

(1). The use of urethanes or other foamed plastic as admixture soil stabilizing agents.

(2). The effect of temperature on the foaming process.

(3). The degree of impermeabilization attained by injection of urethane foamed plastics under vacuum condition.

(4). The effect of lunar environment on the admixture stabilization process.

(5) Development of suitable urethane foamed systems for lunar pour or spray-on applications.

Feasibility Study of Admixture Soil Stabilization With Phenolic Resins

by

T. Durgunoglu and J. K. Mitchell

SUMMARY AND CONCLUSIONS

The feasibility of the use of phenolic resins as admixture stabilizing agents was investigated. The purpose was to determine whether a chemical resin system less expensive than the urethanes could be used for soil stabilization.

The chemistry of phenolic resins, analytical laboratory procedures, and experimental laboratory procedures were investigated.

Hardening mechanisms of the resin system were studied using different amounts of acidic and basic catalysts. An amount of sulfuric acid as an acidic catalyst sufficient to produce a pH value less than 2.0 resulted in satisfactorily cured resins in the absence of soil. However, the use of basic catalysts did not yield a satisfactorily hardened resin.

Several systems were developed which, on theoretical grounds, appear to offer some potential for soil stabilization. However, soils treated with these materials were not satisfactorily stabilized. The probable cause of this poor performance was the inclusion of large amounts of water in the resin system.

RECOMMENDATIONS

It is recommended that resin systems be developed that avoid the inclusion of excess water in the treated soil system. Powder resin forms may be suitable.

Mechanics of Rolling Sphere—Soil Slope Interaction

by
H. J. Hovland and J. K. Mitchell

SUMMARY AND CONCLUSIONS

Conclusions from this research pertain to the failure mechanism of rolling sphere-soil slope interaction, a theory developed to account for this interaction, a proposed method for evaluating the friction angle of lunar soil, and properties of the lunar regolith as determined from boulder track records. These items are summarized below.

Failure Mechanism

The soil failure mechanism associated with rolling sphere-soil slope interaction was investigated using models and by testing an instrumented spherical wheel for determination of the distribution of contact pressure along the sphere-soil interface. As a sphere rolls down a sand slope, the most important characteristics of behavior are:

1. Track formation is accompanied by soil volume changes and shear deformations.
2. For loose sands and at the beginning of rolling in general, soil deformations consist of volume change.
3. When volume change (compression) can no longer account for all the soil that must be displaced, shear planes develop.
4. Within the shear zone in front of the sphere there may be about two shear planes per cm of depth of the shear zone.
5. The shearing is a discontinuous process although rolling appears to be continuous to the naked eye. Separately identifiable shearing soil wedges are pushed out in front of the sphere. These failure wedges appear to form where the

soil is weakest; sometimes directly in front of and sometimes slightly to the sides of the sphere.

6. The contact pressure distribution is bell-shaped and can be closely approximated by a parabolic function.
7. The maximum pressure beneath the sphere is about twice the average pressure, and the maximum pressure appears to control the development of shear failure.
8. Vertical sections within the soil are bent forward. This forward movement is pronounced; very little lateral movement takes place.
9. The magnitude of the resultant of soil reaction can usually be considered equal to the weight of the sphere. The direction of the resultant can be assumed vertical for practical purposes.

Theory

Based on an understanding of the failure mechanism, bearing capacity theory was modified and additional theory developed to explain the rolling sphere phenomenon. This led to three equations which can be combined to solve for parameters of interest. These equations are:

$$\frac{q_e}{w\gamma_s} = 0.188\ N_{\gamma s} + 1.1 \left(\frac{c}{w\gamma_s}\right) N_{cs} + 0.55 \left(\frac{z}{w}\right) N_{qs} + \frac{q_I}{w\gamma_s} \tag{1}$$

$$\frac{q_e}{w\gamma_s} = \frac{4}{3}\,\frac{\left(\gamma_r/\gamma_s\right)}{\left(w/D\right)^3} . \tag{2}$$

$$\frac{w}{D} = \sin 2\alpha . \tag{3}$$

Equation (1) expresses the total soil resistance in earth gravity, Equation (2) expresses the applied pressure in earth gravity, and Equation (3) expresses the relationship between the w/D ratio and the minimum slope angle required for rolling. In lunar gravity, replacing γ_s by $\gamma_s/6$, Equations (1) and (2) become:

$$\frac{q_m}{w\gamma_s} = 0.0314\, N_{\gamma s} + 1.1\left(\frac{c}{w\gamma_s}\right) N_{cs} + 0.0916\left(\frac{z}{w}\right) N_{qs} + \frac{q_I}{w\gamma_s}\ . \tag{4}$$

$$\frac{q_m}{w\gamma_s} = \frac{2}{9}\,\frac{\left(\gamma_r/\gamma_s\right)}{\left(w/D\right)^3}\ . \tag{5}$$

In the above equations,

c = apparent cohesion

D = diameter of sphere or boulder

q_e = unit soil resistance in earth gravity

q_I = unit soil resistance due to inertia of moving soil

q_m = unit soil resistance in lunar gravity

w = crest-to-crest track width

z = track depth based on crest-to-crest track width

α = slope angle

γ_r = rock or sphere density in earth gravity.

γ_s = soil density in earth gravity.

$N_{\gamma s}$, N_{cs}, and N_{qs} are bearing capacity factors for rolling spheres.

They are defined by:

$$N_{\gamma s} = \left(0.37 + 0.25\,\frac{w}{D}\right)^2 N_{\gamma}, \tag{6}$$

$$N_{cs} = \left(0.37 + 0.25\,\frac{w}{D}\right) N_c, \text{ and} \tag{7}$$

$$N_{qs} = \left(0.37 + 0.25\,\frac{w}{D}\right) \tan\phi\, N_c + 1, \tag{8}$$

where N_{γ} and N_c are general bearing capacity factors for an infinitely long footing on a slope as determined by Meyerhof (1951).

Track formation was predicted from the above theory, and compared with experimental data. This comparison is shown in Figure 6. (The curves are theoretical; the points are experimental.) This comparison confirms the validity of the developed theory for the range of sphere and soil conditions investigated.

Method for Solving for ϕ from Lunar Boulder Tracks

Using Equations (3), (4), and (5), graphs were prepared from which the friction angle, ϕ, of lunar soil can be determined directly from boulder track records. These graphs are presented in Figures 7 and 8. Provided assumptions regarding other soil and rock parameters are realistic and measurements of boulder and track dimensions are adequate, the proposed graphs should give friction angles comparable to ϕ determined from conventional triaxial tests.

Properties of the Lunar Regolith

The following conclusions seem to be appropriate from the results of 69 lunar boulder tracks investigated:

1. The value of ϕ ranged from 19 to 53 degrees with the majority being between 24 and 47 degrees.

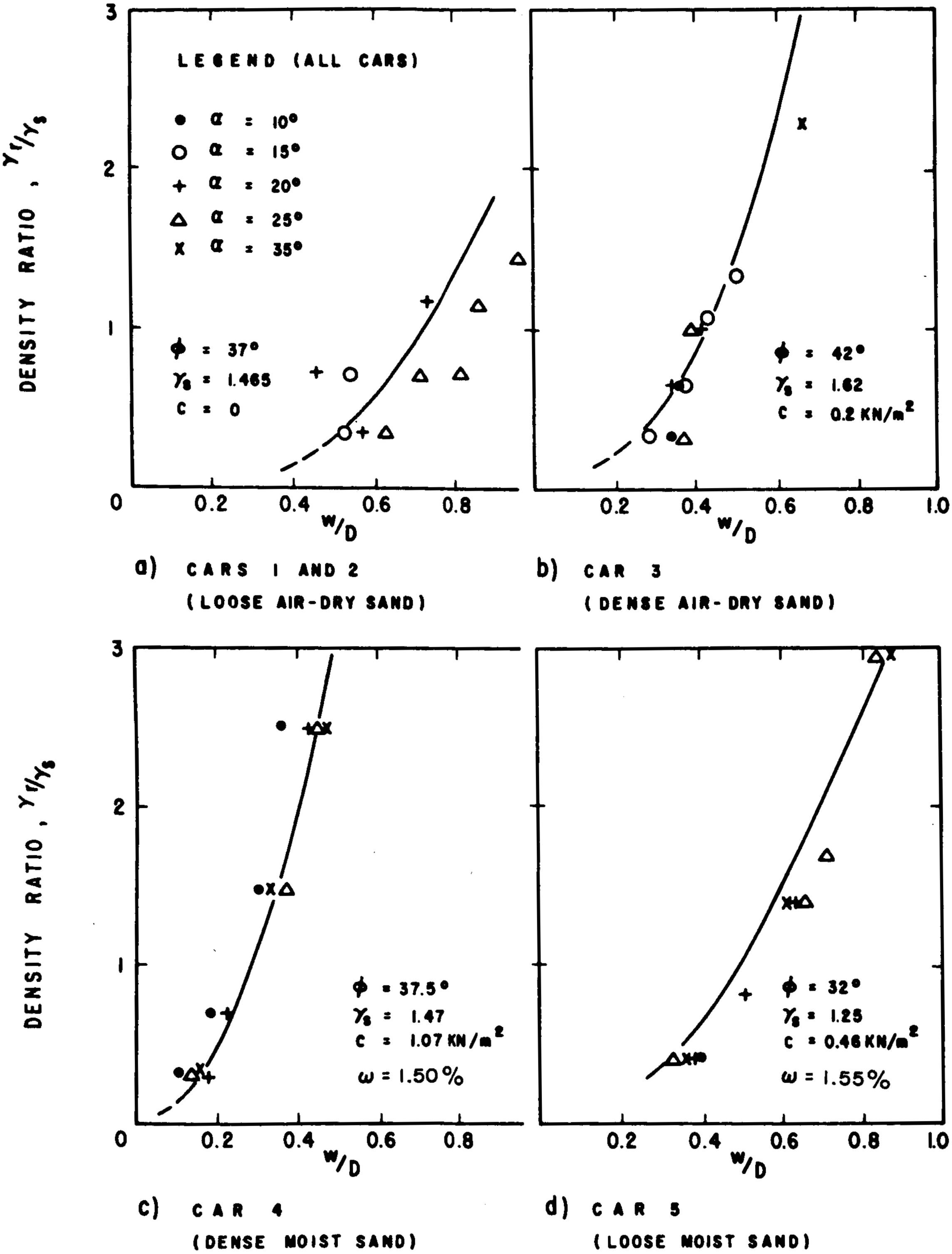

Fig. 6. Density ratio vs. track width over diameter ratio for spheres rolling on Yuma sand.
(Curves are theoretical for α_{min} required for rolling, points are experimental.)

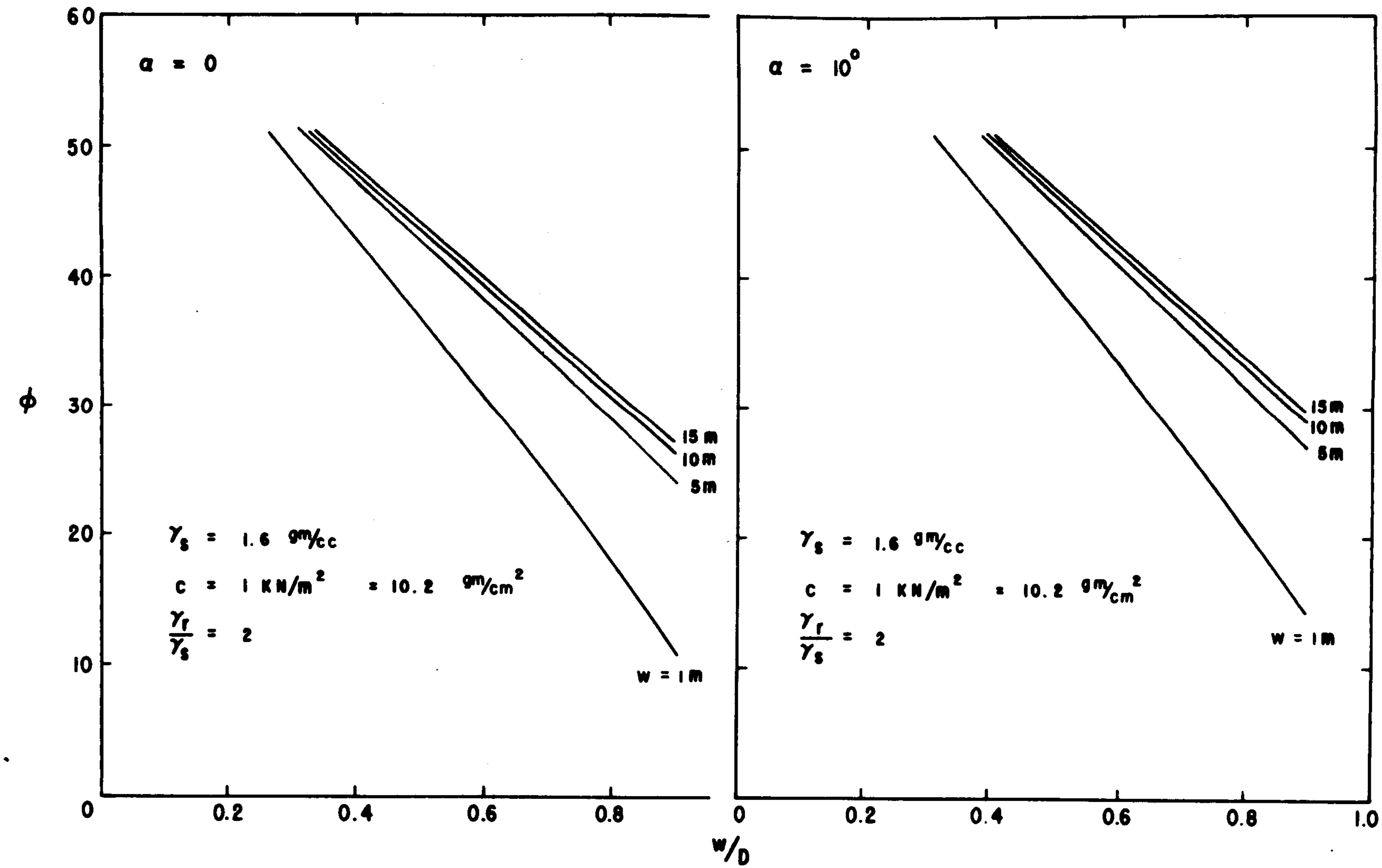

Fig. 7. Influence of friction angle on track width to sphere diameter ratio.

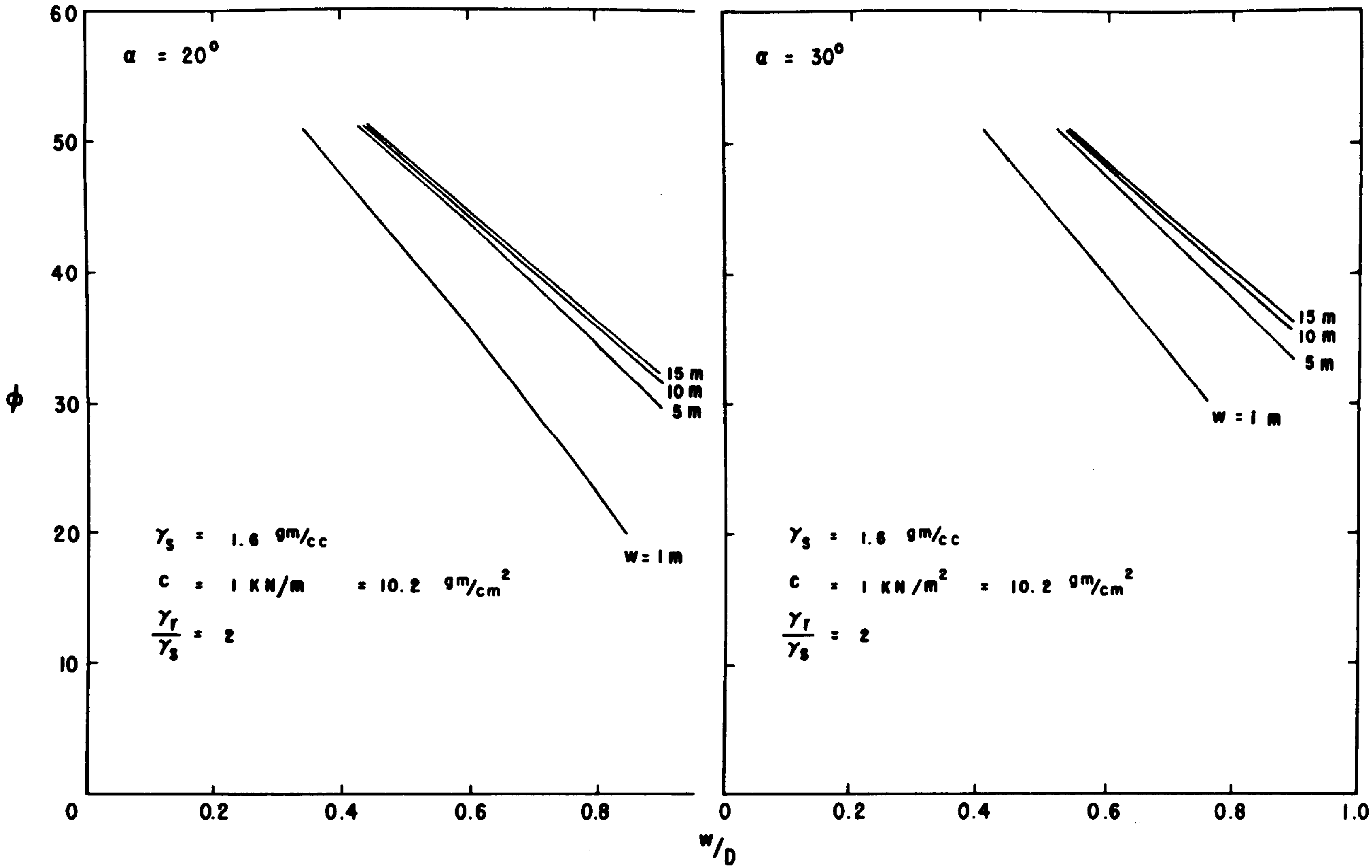

Fig. 8. Influence of friction angle on track width to sphere diameter ratio.

2. The average friction angle, ϕ, was found to be 37 degrees.
3. Based on the range of ϕ, lunar soil conditions appear to be quite variable.
4. Soil density, cohesion, and friction angle probably increase with depth below the lunar surface.

Possible implications of the range of ϕ reported above for the boulder tracks from different areas of the moon are:

1. The state of soil compaction of lunar soil may vary.
2. The cohesion may vary.
3. The friction angle may vary.
4. The measured track width, which is the basis for the range of ϕ, was not representative of the crest-to-crest track width immediately after the track was formed.

Of the above possibilities, undoubtedly some of the track widths were not representative of the crest-to-crest track width immediately after the track was formed. On the other hand, some variability of soil conditions should be expected. Particularly, the state of compaction of the lunar regolith may vary.

In applying the proposed theory to the solution of lunar boulder-track problems, it should be remembered that inertia forces are relatively more important on the moon than on earth. For the 69 lunar boulder tracks investigated, soil inertia was considered to provide 20 per cent of the total soil resistance.

RECOMMENDATIONS

It is recommended that the boulder track method be considered as a remote reconnaissance technique for preliminary study of soil conditions at different points on the moon and on other planets where boulder tracks are observed.

It is recommended that efforts in the near future be directed also to a study of wheel-soil interaction. It is believed that the failure mechanism described is applicable to many wheel-soil interaction problems. With some modifications, the proposed theory may be suitable for the study of wheels. Since much data are already available in the literature on wheel-soil interactions, it might be possible to check the proposed theory without extensive testing. Such studies are recommended.

Borehole Probes

by

R. E. Goodman, K. Drozd, S. Chirapuntu, H. J. Hovland, and T. K. Van

SUMMARY AND CONCLUSIONS

Previous research explored the applicability of various devices for measurement of load-deformation properties of soils and rocks in lunar boreholes. In this investigation: 1) the theory necessary for measurement of rock strength in boreholes was completed and checked by laboratory studies; and 2) a borehole jack basically suited for the lunar problem was designed, built, and tested on simulated lunar soils.

The Borehole Tensile Strength of Rock

Borehole jack tests can be used to determine the strength of the borehole wall rock as follows:

$$T_B = \frac{K_T P_F}{R} ,$$

where:

T_B = the borehole tensile strength (force/area) determined by the borehole jack;

K_T = a dimensionless stress concentration factor depending on the jack design (values are presented in the detailed technical report);

P_F = the jack load, per unit of plate length, at the time the load-deformation curve begins to curve downward; and

R = the radius of the borehole.

Application of this approach for concrete and rock without an included crack initiation detection device (such as rock noise detector) yielded a value for strength 2.5 to 3 times higher in comparison with the rupture strength in bending of rock and concrete beams. The amount of discrepancy is typical in comparing rupture points with crack initiation points under compressive load, simply because an initiated crack does not prove a fatal flaw in the compressive mode until it has grown a specified amount by further load application. The factor L_R = 2.5 to 2.9 was therefore incorporated; i.e., the borehole jack strength, when divided by L_R yields the borehole flexural strength.

Lunar Borehole Jack

A prototype jack adapted to the characteristics of lunar boreholes (but not yet lunarized) was designed and tested in lunar soil simulant. The jack operates in a 2-inch-diameter borehole and permits 3/4-inch plate displacement. The testing plates were made five to six times longer than the borehole diameter to approach plane strain conditions. Figure 9 shows the assembled jack; the curved surfaces are the plates spread out laterally at the time the jack is loaded.

The testing apparatus, including a steel chamber, electrical instruments, and the borehole jack, are shown in Figure 10. Tests were conducted (in earth environment) inside the cylindrical steel chamber filled with simulated lunar soil. The chamber was pressured longitudinally, by three pistons acting on a steel end plate, to simulate depth of burial under plane strain conditions.

Jack pressure-deformation curves were obtained for each test using an x-yy' plotter. An example of such a curve is shown in Figure 11. The lower portion of this figure shows a curve obtained with the jack out of the borehole; it gives the resistance caused by

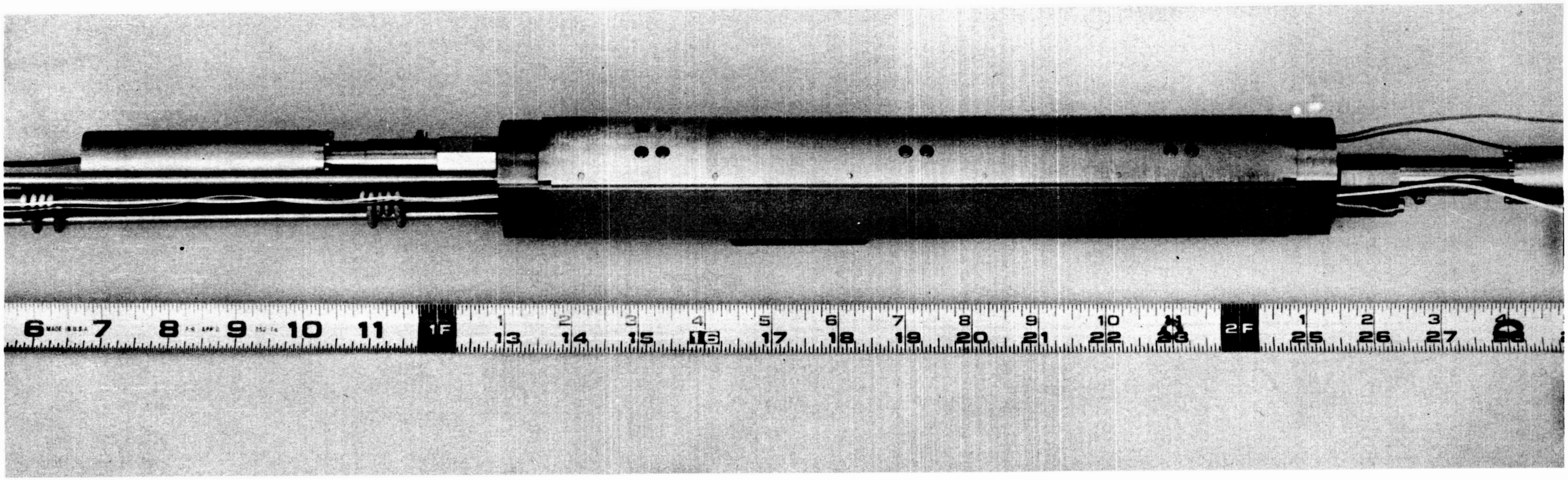

Fig. 9. Assembled lunar borehole jack.

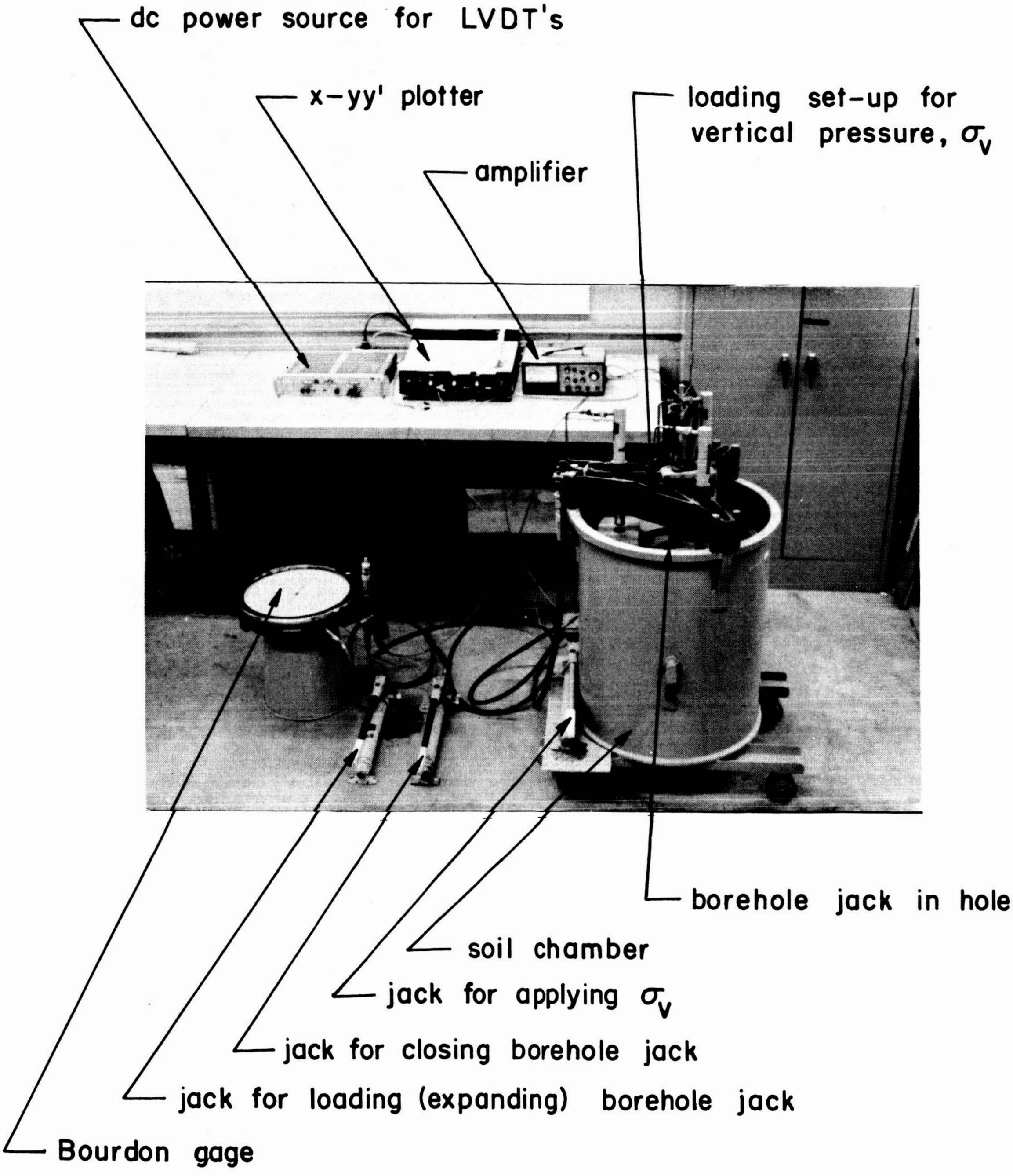

Fig. 10. Assembly of borehole jack test setup.

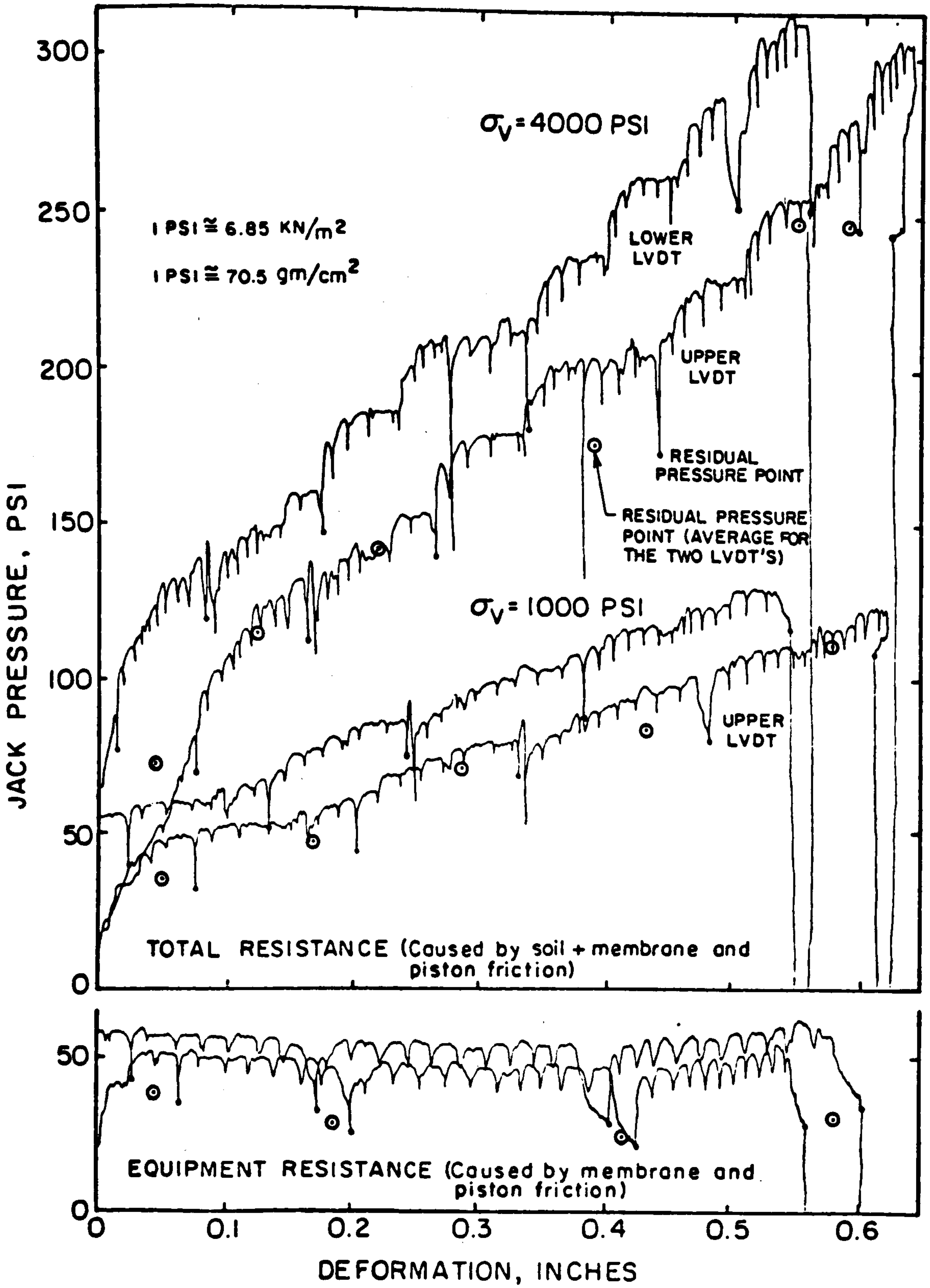

Fig. 11. X-YY' plot of pressure vs. deformation.

the rubber membrane and piston friction only. The upper curves show both soil resistance and resistance associated with the equipment.

Figure 12 shows the modulus of deformation values determined by borehole jack tests as a function of confining pressure (depth effect) and void ratio. The relatively small scatter and the regularity of the curves are encouraging. Also, the results of the deformation modulus compare favorably with results of plate load tests conducted by Houston, Namiq, Mitchell, and Treadwell (Vol. I, Chap. 1, Detailed Technical Report).

Provided some additional testing in simulated lunar soil and some improvements in the equipment are undertaken, the borehole jack or a similar device could be used to estimate properties of the lunar subsurface materials. This would be possible by comparing the curve obtained in situ on the moon with curves obtained from experimenting with the LSS No. 2. On such a basis, one could estimate in situ soil density and void ratio.

From the results of many independent studies, it is known that the lunar surface is covered by a layer of fractured rock and particulate matter. Work reported in the Detailed Technical Report, Vol. I, Chap. 1, and Vol. II, suggests that the density of this layer increases with depth. The borehole jack is one device by which the above hypothesis could be verified.

RECOMMENDATIONS

1. Since the pressure required to expand the jack in soil is considerably less than the design capacity of the jack, it may be desirable to design a much smaller and lighter device

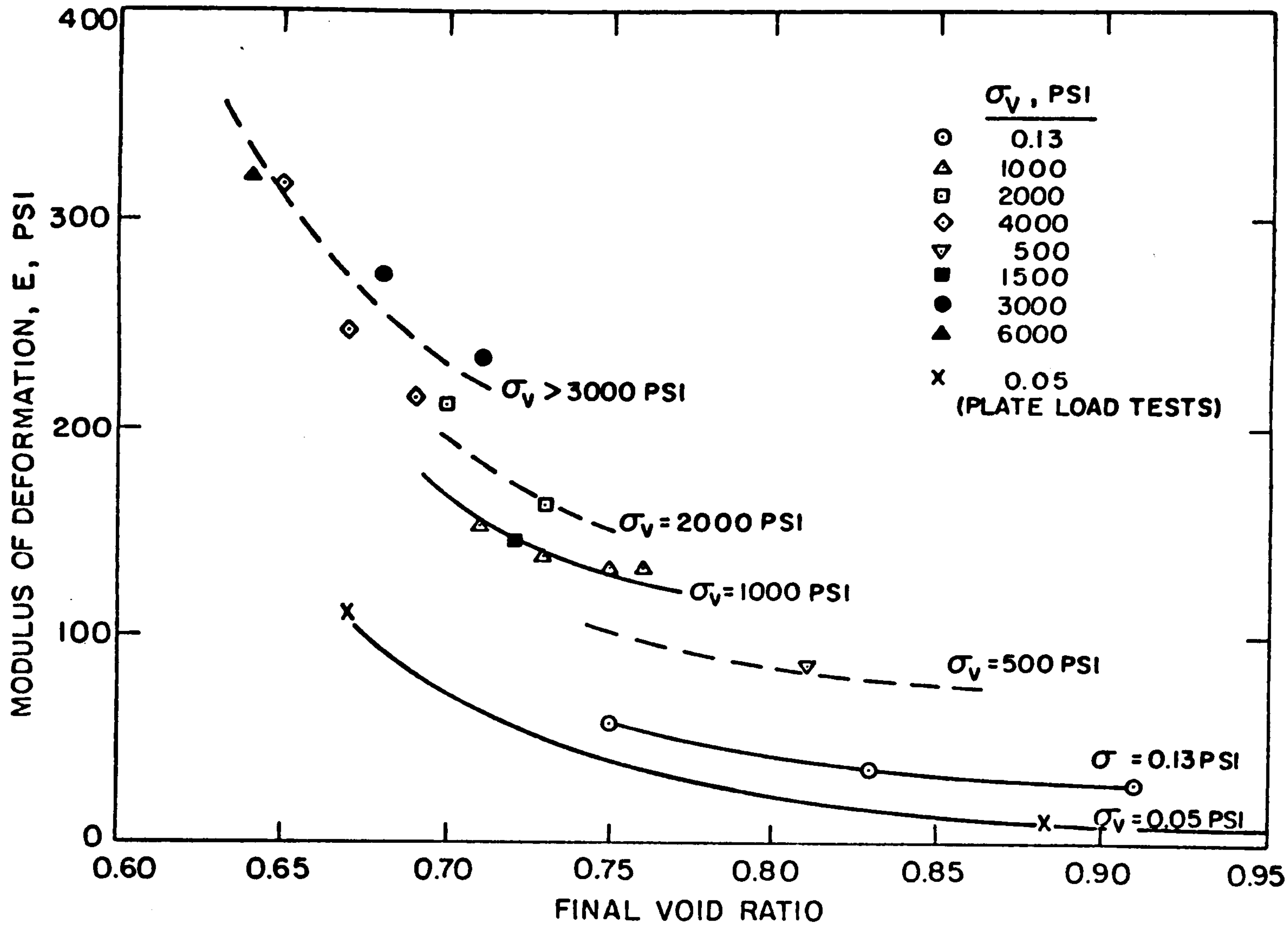

Fig. 12. Deformation modulus vs. void ratio.

for actual lunar use. (The weight of equipment that can be taken to the moon is and will be a limiting factor.)

2. Should such a device be adopted for actual lunar use, additional experimentation would be required and emphasis should be placed on obtaining more precise relationships.

Studies on Fluid Conductivity of Lunar Surface Materials – Theoretical Studies

by

P. Raghuraman and D. R. Willis

SUMMARY AND CONCLUSIONS

Theoretical studies on the problem of developing a probe capable of measuring the fluid conductivity of porous media under lunar conditions have been pursued to consider two principal questions. In the first, we have examined some aspects of the fundamental question as to whether or not the probe could operate in quasi-steady state conditions or whether it will, in fact, be operated while various transient phenomena are still affecting the flow. One aspect of the problem considered was the effect of dead-end pores, which initially contain no gas and act for some time as sinks for mass flow, when gas flows down the open-end pores. A quantity expressing the time required for the outflux from a dead-end pore to be equal to 0.626 times the influx to a dead-end pore was defined as the time constant. Figure 13 shows the time constant as a function of the length-to-radius ratio of the dead-end pores. This figure shows that the time constant tends to a constant as ℓ/a increases. This is a direct consequence of the assumption of diffuse reflection from the wall wherein each wall element reflects to the exit a fraction of the flux coming to the element. If the walls were completely specularly reflecting, the time constant would progressively increase with ℓ/a. Most surfaces are partly diffuse and partly specularly reflecting. It is therefore reasonable to anticipate results for real surfaces similar to our theoretical prediction (Figure 13).

In the second place, we focused our efforts on evaluating the degree of sophistication necessary to analyse the flow through a porous media with vacuum as one of the boundary conditions. A sudden freeze model

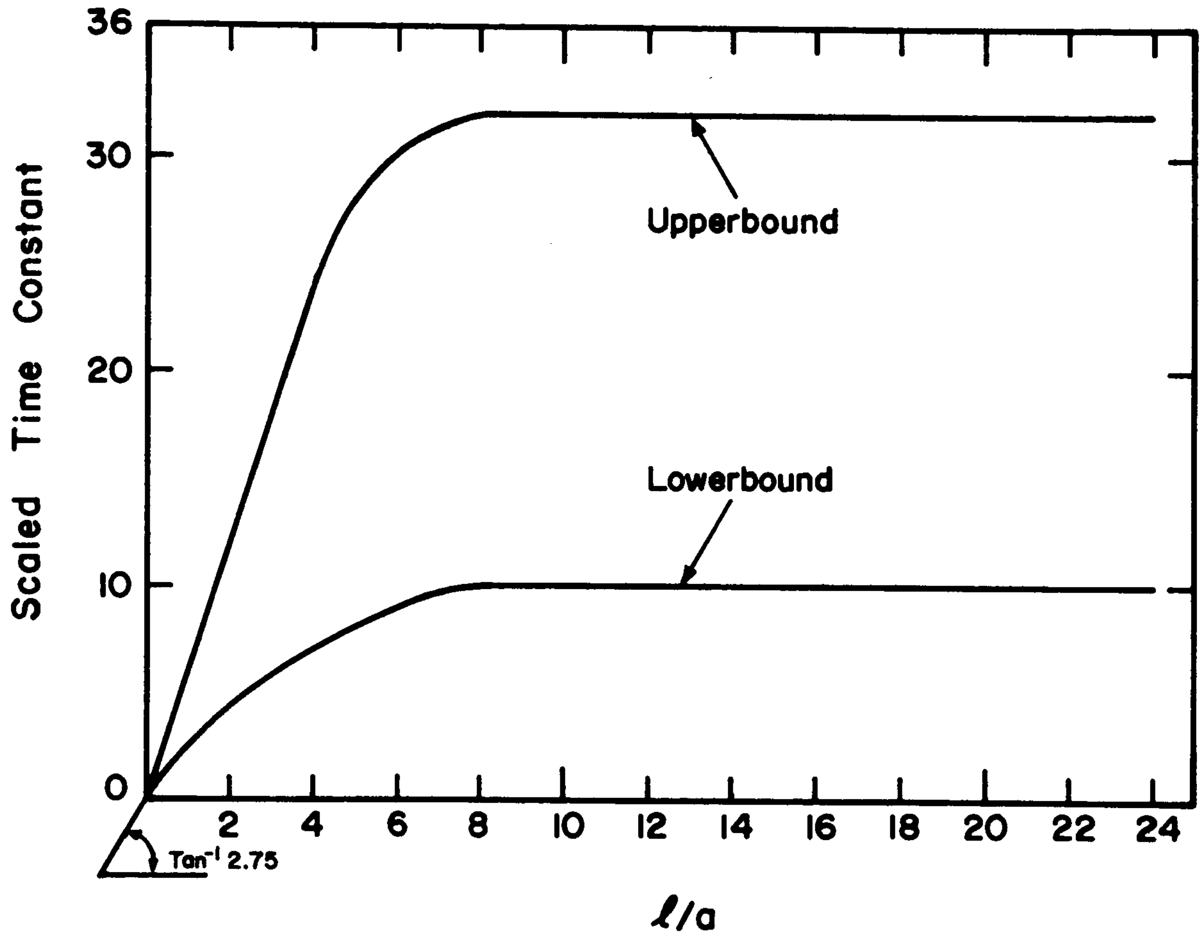

Fig. 13. Variation of time constant with length of radius ratio.

was proposed for the flow and was applied to various models of the porous media. On the basis of present estimates of the lunar pore sizes, it was concluded that the continuum equations could be safely used with very little resulting error.

RECOMMENDATIONS

It is believed that the developed theory satisfies the present needs of our experimentation, and that further theoretical studies are not required.

Studies of Fluid Conductivity of Lunar Surface Materials— Experimental Studies

by
F. C. Hurlbut, C. R. Jih, and P. A. Witherspoon

SUMMARY AND CONCLUSIONS

An apparatus to study the permeability of porous media under rarefied gas flow conditions has been constructed, and preliminary observations of its behavior have been made. With this equipment, studies will be conducted on one-dimensional flows through homogeneous, simulated rock samples having a range of permeabilities. The results of these studies will greatly facilitate the design and understanding of an in situ permeability probe for lunar materials. The apparatus is physically associated with the U.C. Berkeley rarefied gas wind tunnel and makes use of the wind tunnel pumping system.

It is of particular importance in the present context to study the transition regime of flows, for which the Knudsen number, based on pore size, is of order unity. It was an objective of the design of the equipment that it should permit the detailed examination of pressure as a function of position along the rock specimen. Accordingly, the apparatus is arranged to contain a segmented specimen, each segment being a circular slab of porous material. The segments are spaced along a cylindrical chamber and sealed to the inner wall of that chamber by means of "O" rings. The chamber wall contains a pressure tap at each gap between specimen segments. A gas source permits a measured flow to enter the specimen under rarefied flow conditions and to pass through all segments before entering the wind tunnel pumping system.

Preliminary measurements were made on a set of four cast-concrete segments to gain operational experience with the instruments and to

develop a physical sense for the appropriate permeability ranges of future specimens. The apparatus behaved well in all regards and appeared to have the capability of giving results of the desired quality. However, no useful quantitative information resulted owing to the low permeability of the specimens tested. Since it is desired to extend the region of transition flow over several slabs, each somewhat less in thickness than that region, it is becoming evident from these observations that specimens must be constructed having much higher permeability than those initially tested.

RECOMMENDATIONS

It is recommended that experimental studies as described herein be further pursued. Within the next few months it will be our objective to complete measurements enabling the description of transition flows in porous media. Interpretation of these results will require the independent characterization of the medium in terms of pore size and configuration. Such characterization will be accomplished by a combination of optical and displacement methods and by a knowledge of the size and configuration of particles (beads, rods, etc.) used for the preparation of each sample. Materials of various descriptions will be formed into specimen slabs, with sintering being viewed as the most promising technique at this time. Thus, one may summarize by stating that the next phase of investigation should consist of four essential parts: 1) the preparation of suitable samples, 2) the physical characterization of these samples, 3) the measurement of flow characteristics, and 4) the interpretation of results.

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