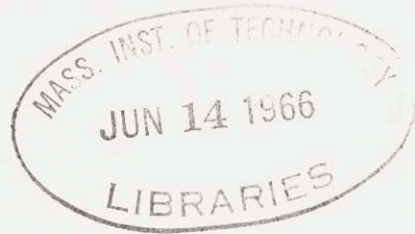FRICTIONAL CHARACTERISTICS

OF QUARTZ

by

JOSEPH W. DICKEY

Submitted in Partial Fulfillment

of the Requirements for the

Degree of Bachelor of Science

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June, 1966

Signature of Author:.................. Signature redacted ....
Department of Chemical Engineering, May 20, 1966

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Thesis Supervisor

Accepted by:........... Signature redacted ....
Head of Department

Department of Chemical Engineering
Massachusetts Institute of Technology
Cambridge 39, Massachusetts
May 29, 1966

Professor William C. Greene
Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge 39, Massachusetts

Dear Professor Greene:

In accordance with the regulations of the Faculty, I herewith submit
a thesis, entitled "Frictional Characteristics of Quartz," in partial
fulfillment of the requirements for the degree of Bachelor of Science
in Chemical Engineering at the Massachusetts Institute of Technology.

Respectfully submitted,

Signature redacted

Joseph W. Dickey

ACKNOWLEDGEMENTS

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I. SUMMARY

The purpose of this investigation was to study the frictional characteristics of quartz surfaces. Direct shear tests were used to determine the friction between two quartz blocks, having an area of approximately 1.9 sq. in. for the contact face. Tests were run both dry and submerged (in distilled water) with varying conditions of surface roughness and surface cleanliness.

The results of this investigation indicate that the magnitude of the coefficient of friction for quartz is a complex function of both surface roughness and surface cleanliness. The coefficient of friction (μ, defined as frictional or shear resistance divided by normal force) increases with increasing surface cleanliness. The effect of increasing surface roughness is to decrease friction on very clean surfaces and to increase friction on dirty surfaces.

Coefficients of friction as high as $\mu = 1.06$ have been measured on very clean, smooth quartz surfaces. This is very likely not the highest value or friction obtainable for quartz surfaces. Quartz surfaces cleaned under the best cleaning procedures still showed evidence of a contaminating surface layer.

II. INTRODUCTION

A. Purpose of the Investigation

The stability of masses of soil and of particulate systems is significantly influenced by the frictional characteristics of the particles composing the system. In a mass of soil the peak friction angle, ϕ_m, is influenced by three factors ([1]): (1) the magnitude of particle-to-particle friction, ϕ_μ; (2) the dilatancy, or the energy required to cause a volume change during shear; and (3) the amount of rearranging of particles during shear. The purpose of this investigation will be to study the nature of particle-to-particle friction and the factors that influence the magnitude of the particle-to-particle friction angle.

B. Scope of the Investigation

The investigation was limited to a study of quartz, the most prevalent mineral found in granular soils. The test program primarily involved the determination of the effects of surface moisture, surface roughness and surface cleanliness on the frictional resistance developed between flat surfaces of quartz blocks. Various cleaning techniques were used in an attempt to produce high values of friction on dry quartz surfaces at atmospheric pressures. Direct shear tests were used to evaluate the factors in question.

C. Frictional Behavior and the Solid Surface

Frictional behavior generally follows two basic laws:

(1) The frictional force or shear resistance between two bodies is directly proportional to the normal force between the bodies.

(2) The frictional force between two bodies is independent of the total area of the contacting surfaces.

These laws were first proposed by Leonardo da Vinci in the late 1400's. They were forgotten until revived by Amontona in 1699.

Terzaghi (2) proposed a physical explanation for frictional behavior of plastically deforming materials in 1925. A similar hypothesis was independently proposed and further substantiated by Bowden, Moore, and Tabor (3). The resulting theories have been described by Lambe and Whitman (4) as follows:

(1) On a submicroscopic scale, the surface of even a carefully finished body is actually quite rough, and hence two surfaces will only be in contact where the high points tough one another; i.e., over a very small fraction of the apparent contact area: see Figure 1.

(2) Because the actual area of contact is so small, the normal stresses across these contacts will be enormous and will be fixed by the yield strength of the high points. Thus, the total normal force N is:

$$N = A_c q_u \qquad (1)$$

where q_u is the normal stress required to cause yielding (i.e., plastic flow) of the high points. Since q_u is fixed in magnitude, an increase in total normal load between the bodies must mean a proportional increase in the area of actual contact. This increase comes about as the result of plastic flow of the high points.

(3) Adhesion occurs at the points of actual contact: i.e., the two bodies are joined by chemical bonds. Shear resistance is provided by the strength of the material at these points of adhesion. Thus, the maximum possible shear force, T_{max} is:

$$T_{max} = s A_c \qquad (2)$$

where s is the shear strength of the adhered junctions and A_c is the actual area of contact.

Combining equations (1) and (2) gives the relation:

$$T_{max} = \frac{s}{q_u} N \tag{3}$$

As s and q_u are material properties, T_{max} is proportional to N. The coefficient of friction μ should then equal s/q_u. The friction angle ϕ_μ may now be defined as $\tan \phi_\mu = \mu$. This may be seen in Figure 2.

Although the above relations are consistent, it would be more proper to say that A_c is proportional to N for a fixed T_{max}/N. This can be seen through the phenomenon of junction growth with the aid of Figure 3. This also introduces the complexities of surface contaminants.

The effect of the surface contaminants is to make the junctions weaker in shear strength than the original material. The crystal structure of the junction formed by adhesion will be weakened due to the interference of the contaminating atoms that have not been pushed out of the contact area. This weakening will cause the junction to fail while the asperities are still able to transmit normal stress.

The role of surface roughness should play an important part in the determination of the coefficient of friction. Given two very rough surfaces in contact and two relatively smooth surfaces in contact, it can be seen from Figure 4 that shear should be more difficult to initiate in the rough case than in the smooth case. This is due to the necessity of moving the asperities up and over one another in addition to overcoming the mineral-to-mineral frictional resistance.

For rougher surfaces there is less actual contact area per unit of apparent contact area before plastic deformation takes place.

Hence, there is more force per unit of actual contact area. If there is a layer of surface contaminants, it will be easier for a rougher surface to push away the surface contaminants. This would mean that for contaminated surfaces there would be more actual mineral-to-mineral contact (in contrast to mineral-to-contaminant-to-mineral contact) for rougher surfaces. This, too should give higher friction values for rougher surfaces.

1. Frictional Behavior for Elastic Solids

The discussion up to this point has been concerned with plastically deformed solids. For perfectly elastic materials the frictional behavior might be theorized by considering the point of contact between two asperities. If the asperities are assumed to have spherical tips, the following analysis (5) may be used in determining the frictional behavior with the aid of Figure 5.

This analysis predicts a circular contact area of diameter d given by:

$$d = (\delta N \frac{R_1 R_2}{R_1 + R_2})^{1/3} \qquad (4)$$

where R_1 and R_2 are the radius of curvature for the respective asperities and δ is determined by the elastic constants and contact conditions of the material. Assuming that R_1 is large (or ∞) with respect to R_2, this results in contact between a spherical indenter and a plane surface. For this case δ is given by:

$$\delta = \frac{12 (1 - \nu^2)}{E} \qquad (5)$$

where ν is Poisson's ratio and E is the Modulus of Elasticity, both evaluated for the indenting material.

The actual area of contact then becomes:

$$A_c = \frac{\pi d^2}{4} \qquad (6)$$

or $\quad A_c = \dfrac{\pi}{4} \; (\delta R_2)^{2/3} \; N^{2/3} = KN^{2/3}$ \hfill (7)

The frictional force will then be

$$T_{max} = sA_c = sKN^{2/3}$$ \hfill (8)

and

$$\mu = \frac{T_{max}}{N} = sKN^{-1/3}$$ \hfill (9)

The coefficient of friction will then vary as $N^{-1/3}$ for elastic solids. However, this analysis is for a single asperity on a flat plane and may not accurately describe the contact conditions when a large number of asperities are involved.

2. The Adsorbed Layer

The surface properties of a solid are to a large extent determined by the nature of the adsorbed or contaminating layer. A qualitative discussion of the adsorbed layer has been presented by Bromwell (6). The properties of structure, thickness, and mobility are of particular importance. However, since the adsorbed layer is on a molecular scale, these properties are difficult to determine directly. As a result these properties are usually inferred from experiments on contaminated, poorly defined surfaces.

The structure of the adsorbed layer may be broken down into the chemically adsorbed layer and the physically adsorbed layer. The chemically adsorbed layer is usually only one molecule (or monolayer) deep. The adsorbed molecules in this first layer are localized, i.e., they are essentially immobile and confined to the sites to which they are chemically adsorbed (7). The chemically adsorbed layer may be expected to have a fixed orientation depending on the bonding characteristics of the solid surface and the adsorbed material. For large organic adsorbates with a large effective area, the area occupied per

molecule may be calculated with a knowledge of the surface area and the point when a monolayer is completed. These molecules can be shown to be stacked upright (hydrophillic) or spread out (hydrophobic) depending on the solid material.

An ideal quartz surface is shown schematically in Figure 6(a). This surface has one anionic and one cationic site per 23.4 $\overset{o}{A}{}^{2}$ of surface (6). The surface is usually assumed to hydrate rapidly as shown in Figure 6(b). The surface can then be made hydrophobic by the addition of dimethyl chlorosilane as shown in Figure 6(c). The resulting surface has a much lower surface energy and should exhibit significantly altered properties.

The physically adsorbed layers can be of varying thickness depending on the total pressure and the partial pressure of the adsorbed material (7). The energy of the molecules in the physically adsorbed layer is less than the energy of the molecules in the chemically adsorbed layer. The molecules in the chemically adsorbed layer have quite different energys owing to the direct interaction with the solid surface. The molecule would be free to move (or mobile) if its energy exceeds the energy due to the surface or surrounding bonding forces. Hence, the chemically adsorbed layer is considerably more immobile than the physically adsorbed layer as it must overcome a stronger bonding energy to the solid surface.

3. Frictional Behavior of Quartz

The question might now be asked as to which theory should be used in determining the friction of quartz, elastic deformation theory or plastic flow theory? The answer to this lies in the deformation behavior of the quartz surface. However, the behavior will vary with the size of the loaded area, the surface roughness, and the magnitude of the load.

A mechanistic description of the deformation of an average quartz surface has been given by Bromwell (6). He suggests that the deformation might be expected to proceed as follows:

(1) When the surfaces are first brought into contact under very light loading, the highest surface asperities will carry the load. If they are few in number, these highest points may deform plastically if the stress, q_u, required to cause permanent deformation is exceeded.

(2) As the loading is increased, more asperities will be brought into play and although the initially highest points may be deforming plastically, most of the load will probably be carried by elastic deformation.

(3) If the surface only makes one contact with each of two adjacent surfaces (the minimum equilibrium conditions), the deformation will depend on the load carried by the particle. At high loads, if the load continues to be carried through a single asperity, this asperity will be plastic.

A recent investigation into the frictional behavior of minerals by Horn (8)(9) has yielded several interesting results. Horn, as well as several previous investigators, found that the friction of quartz was higher when in water than in a dry state. The difference was almost a factor of four, $\mu = 0.11$ dry vs. $\mu = 0.42$ wet.

A possible explanation for this anti-lubricating effect of water on quartz is that the water disrupts the adsorbed films on the quartz surface. The adsorbed contaminating layer would be serving to keep the actual solid surfaces partly separated. The water molecules, being polar, would induce secondary bonding forces in the contaminating

layer, while to a large extent dissolving the physically adsorbed layer. The interaction of the water molecules with the chemically adsorbed layer would increase the energy of the chemically adsorbed layer, thereby making it more mobile. With a more mobile chemically adsorbed layer it would be easier for the actual solid surfaces to come into contact, hence increasing the friction.

Horn (8) also observed that the apparent anti-lubricating effect of water was greater for smooth surfaces than for rough surfaces. This, too, might be explained by the contaminating surface layer. For the smooth surface a relatively thin film of contaminants might give effective lubrication. However, for a much rougher surface the thin contaminating layer is more easily pushed aside as more normal force is transmitted over a smaller surface area.

Bromwell (10) investigated the frictional properties of mineral surfaces in high vacuum. He concentrated on the effects of surface cleanliness on frictional resistance. The results of his investigation indicate that at least for smooth surfaces, friction is greatly dependent upon the degree of surface cleanliness. The friction could be increased or decreased by changing the cleaning procedure or by the use of high-vacuum equipment. Figure 7 shows some of the results obtained by Bromwell, Horn, and others.

Bromwell (10) also found that frictional resistance due to changes in surface roughness cannot be accurately studied independently of surface cleanliness. Identical cleaning procedures apparently did not produce the same degree of surface cleanliness on smooth and rough surfaces. This resulted in lower values of friction for rough surfaces than for smooth surfaces. For surfaces cleaned as in line No. 8,

Figure 7, he found $\mu = 0.75$ for smooth surfaces and $\mu = 0.61$ for rough surfaces.

The investigations by Horn and Bromwell illustrate that much remains to be found about the mechanisms of frictional behavior. There is such a large number of variables that it is extremely difficult to isolate these variables and determine their individual effect on frictional behavior. The effect of surface cleanliness upon frictional resistance is so great that extreme care must be exercised in all testing procedures if accurate or repeatable results are to be obtained.

N   plastic zones around
     actual contacts
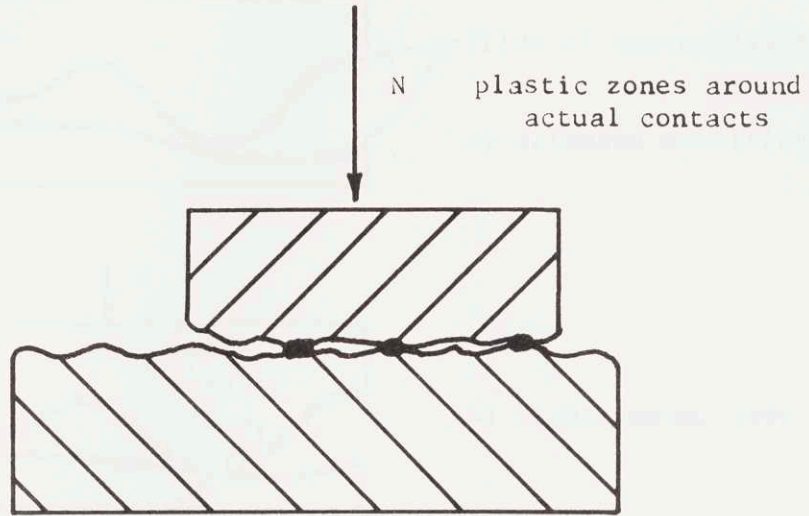
(after Bowden & Tabor, (11))

FIGURE 1. ACTUAL CONTACT BETWEEN "SMOOTH" SURFACES.

$$T_{max} = \mu N$$

$$\tan\phi_\mu = \frac{T_{max}}{N} = \mu$$
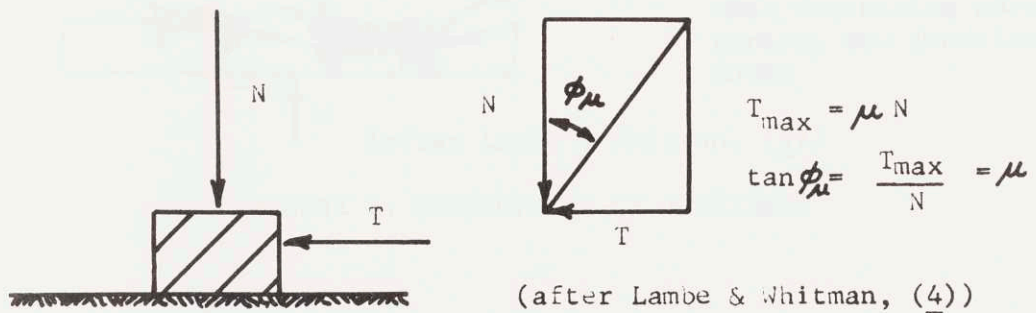
(after Lambe & Whitman, (4))

FIGURE 2. DEFINITION OF THE FRICTION ANGLE ϕ_μ.

films of contaminants

a) Unloaded condition

N

some
plastic
flow

b) Light normal load

N contaminants mostly squeezed out

N

deformed
zones

c) Increased normal load;
plastic flow at contact
with constant normal
stress

N cold weld weakened by
remaining contaminants

N   T

Normal stress
decreasing

d) Shear stress applied;
further plastic flow
with decreasing normal
stress: new junction
forms

T   N

(after Lambe & Whitman, (4))

FIGURE 3. DEVELOPMENT OF JUNCTIONS
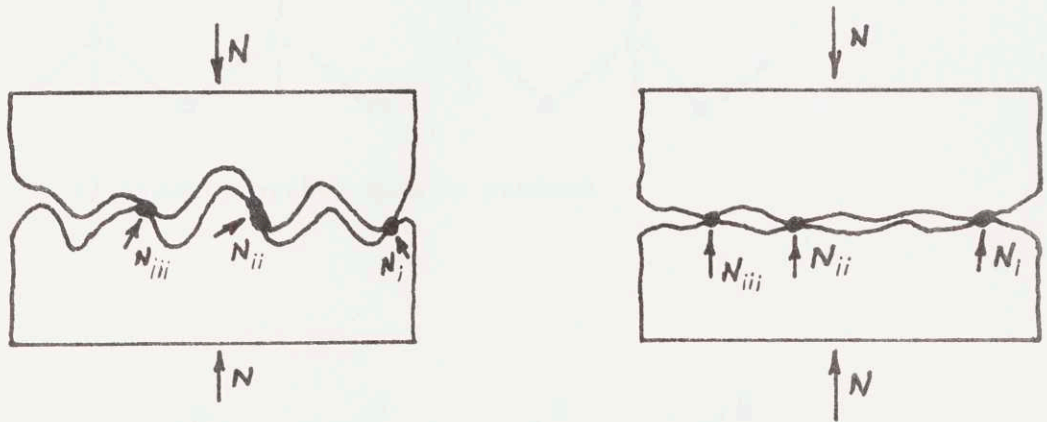
i) Before shear motion
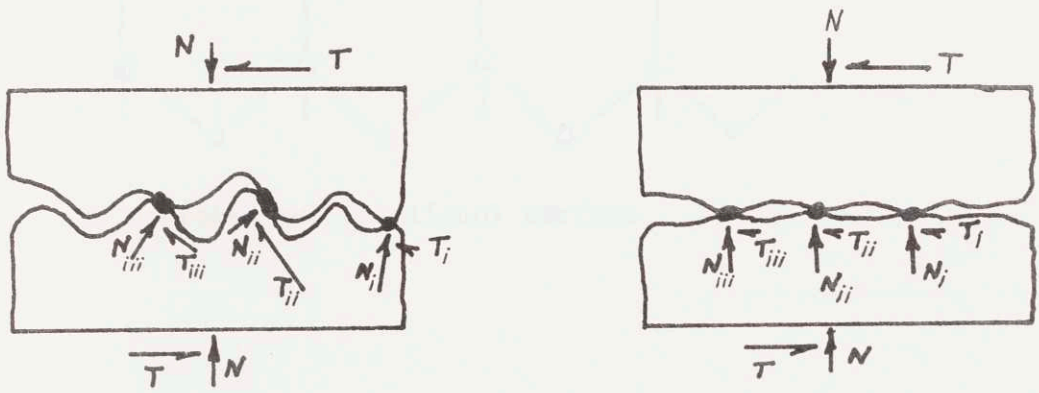
a) Rough surfaces   b) Smooth surfaces

ii) After shear motion

FIGURE 4. THE ROLE OF INTERLOCKING

FIGURE 5. CONTACT BETWEEN ELASTIC SOLIDS
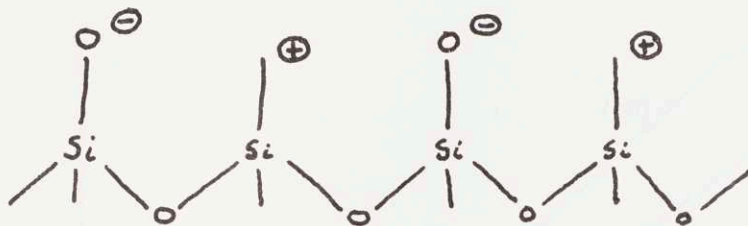
a) Freshly broken quartz surface
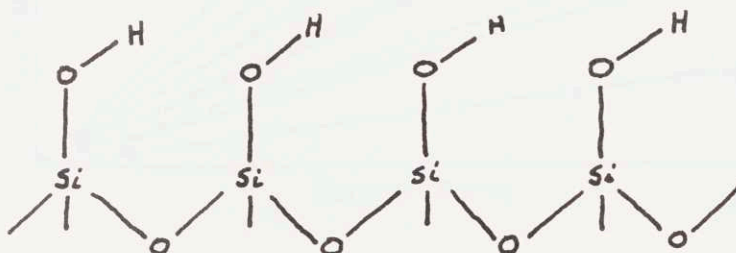
b) Hydrated quartz silanol surface
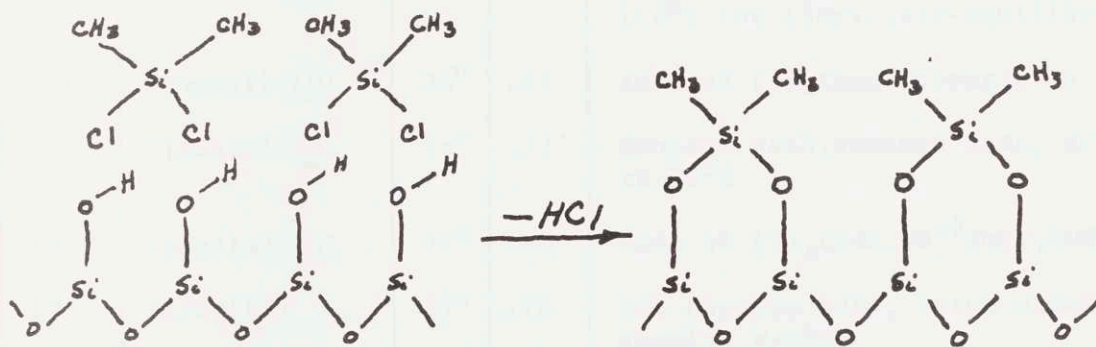
c) Hydrophobic quartz surface

(after Bromwell, (6))

FIGURE 6. THE SURFACE OF QUARTZ

FIGURE 7. EFFECT OF SURFACE CLEANLINESS ON FRICTION OF SMOOTH QUARTZ

(after Bromwell (10))
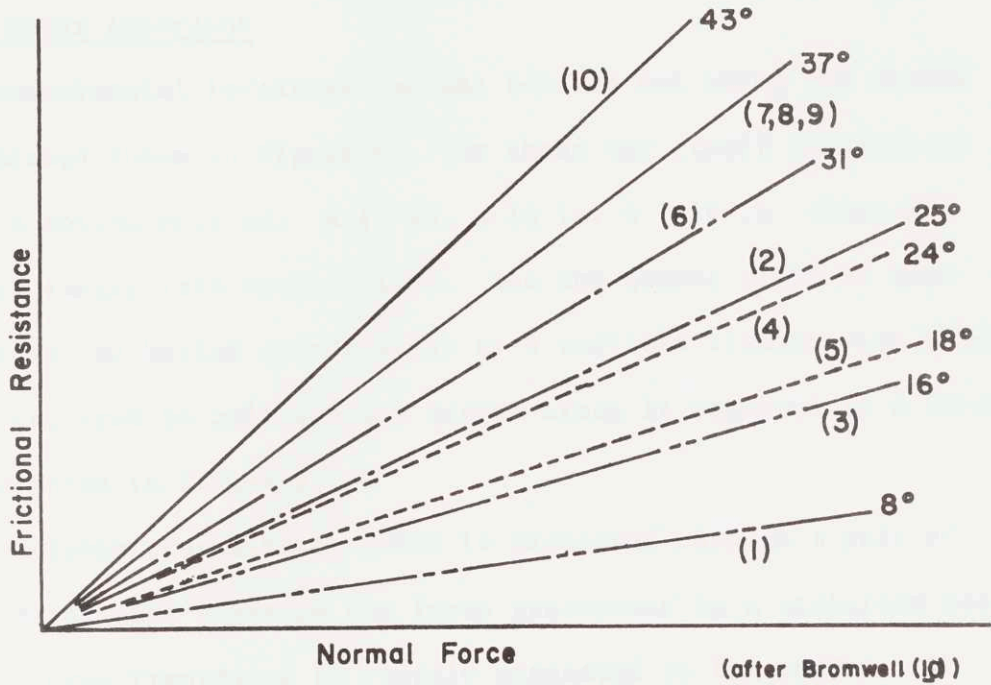
LINE NO.	INVESTIGATOR	ϕ_μ	μ	TREATMENT
(1)	Horn(8)	8°	.14	Acetone wash, detergent wash, 110°C for 24hrs.,air-equilibrate
(2)	Horn(8)	25°	.46	same as (1),then submerge in H_2O
(3)	Bromwell(10)	16°	.30	Acetone wash, detergent wash, 110°C for 12hrs.,air-equilibrate
(4)	Bromwell(10)	24°	.45	same as (3),then submerge in H_2O
(5)	Sjaastad(14)	18°	.33	Benzene wash,acetone wash, dry at 70°C
(6)	Sjaastad(14)	31°	.60	same as (5),then 10^{-5}torr,200°C
(7)	Hardy(15)	37°	.76	Hot chromic acid, scrub under running water
(8)	Bromwell(10)	37°	.75	Trichloroethylene rinse, acetone rinse,detergent wash,distilled H_2O rinse,methyl alcohol rinse,acetone rinse, very careful handling
(9)	Bromwell(10)	37°	.75	same as (8),then submerge in H_2O
(10)	Bromwell(10)	43°	.93	same as (8),then 10^{-8}torr,350°C

III. PROCEDURE AND APPARATUS

A. APPARATUS

1. Direct Shear Apparatus

The experimental investigation was carried out using the direct shear apparatus shown in Figure 8. The shear box itself consists of a top and a bottom section. A 1½ in. x 1½ in. x 7/16 in. block of quartz fits snugly into each section. The top quartz block is then pulled across the bottom quartz block by a variable transmission motor. The force required to pull the top quartz block is measured by a force transducer shown in Figure 9.

The variable transmission motor is connected through a pair of speed reduction gear boxes to the force transducer by a stainless steel wire. The force transducer is rigidly connected to the shaft. The shaft and bearings provide support for the yoke and transducer. The yoke is rigidly connected to the shaft on one end and is connected to the top section of the shear box by a stainless steel wire on the other end.

The bottom section of the shear box and the two ball bushing housing blocks are bolted to the base plate. The base plate is milled flat and to the same level where these pieces are connected. This is necessary to assure that the line of action passes through the quartz contact surface, the wire connection between the top shear box section and the yoke, the center line of the shaft, and the wire connection between the transducer and the gear box. This is desirable in order to eliminate any moments that might tend to either separate the quartz surfaces or push them together.

Side panels were heli-arc welded to the portion of the base plate containing the shear box. This forms a water tight box for running submerged shear tests. Heli-arc welding, as opposed to other types of welding using filler materials, was necessary to prevent corrosion at the joints under the action of cleaning fluids or even atmospheric exposure.

The force transducer is wired to send an electrical signal to an X-Y recorder. The use of the recorder gives a good representation of the "stick-slip" motion during shear. This motion is caused by differences in magnitude between the static and kinetic friction. As the shear force is slowly increased, the sample will remain stationary or will not shear until the static friction is surpassed. The quartz will suddenly shear or "slip" and the shear force present on the surface interface will decrease below the kinetic or sliding friction value.

The quartz samples are cut from large 6 in. x 2 in. x 2 in. single crystals by a commercial firm. The high purity quartz crystals were grown for use as piezoelectric material by Western Electric Co. Four sample blocks $1\frac{1}{2}$ in. x $1\frac{1}{2}$ in. x 7/16 in. may be obtained from a single large crystal. The top block is chamfered 1/16 inch all around to give a constant gross contact area between the top and bottom blocks during a test.

A changing gross contact area might possibly produce undesirable effects. The following condition might be imagined to exist. A large number of asperities are in contact with a constant normal force. Some of the asperities are elastically deformed and some are plastically deformed. As the sample is sheared, the front edge of the top block and the rear edge of the bottom block will not be transmitting any

normal force. Thus, the normal force that the asperities in these regions were supporting will be transfered to the asperities in the central region of the blocks. This added normal force might then plastically deform some of the previous elastically deformed asperities. This will then change the friction or the shear force as the gross area is decreased.

The normal load or force is applied by a hanger rig. This hanger rig rests on the top section of the shear box and hangs through the table on which the base plate is mounted. The dead weights may then be placed on the hanger. A more detailed description of the apparatus may be found in Appendix A.

2. Surface Roughness Measurement Apparatus

Measurements of surface roughness were made on several representative sample blocks. The instrument used was a "TALYSURF 4", which employs a sharply pointed diamond stylus (0.0001 in. tip diameter) to trace the profile of the surface irregularities (12). A flat shoe (¼ in. x 1/16 in.) is used to provide a datum, as shown in Figure 10. The stylus and shoe are pulled across the surface by a motorized unit. The up and down movements of the stylus cause an electrical current to be transmitted to either a graph recorder or an Average Meter. The maximum magnification is 100,000 X, giving a full scale range on the chart of 20 μ in. and a full scale range on the Average Meter of 2 μ in.

The Average Meter gives the "center-line-average" (C.L.A.). The center-line is a line parallel to the general direction of the profile for which the area enclosed by the surface profile above and below the line are equal, as shown in Figure 11 (13). This line is found

automatically by electrical integrating instruments. The center-line-average is the average arithmetic departure of the profile from the center-line. The root-mean-square value is generally 10 percent to 30 percent greater than the C.L.A.

B. TESTING PROGRAM AND PROCEDURE

1. Specimen Preparation

The quartz blocks used in this investigation were finished with a variety of surface roughnesses. Three different roughnesses were used for the majority of the investigation. The first, referred to as smooth, was produced with a No. 600 grit diamond wheel. The second, referred to as rough, was produced with a No. 220 grit diamond wheel. The third, referred to as very rough, was produced with a No. 120 grit diamond wheel.

Three other finishes were produced using horizontal table wheels. The first of these finishes, referred to as polished, was produced using a fine aluminum oxide powder in suspension with water as the polishing agent. The second, referred to as hand-ground smooth, was produced by wet-grinding using a No. 600 grit carborundum paper. The third, referred to as hand-ground rough, was produced by wet-grinding using a No. 240 grit carborundum paper.

The wet-grinding preparation was actually more of a polishing preparation than a grinding preparation. This was because a large percentage of the quartz particles already fractured off of the surface was retained in the grinding paper and performed as grinding material. This "grinding" material with the identical hardness and melting point as the surface produced a polishing effect as it was forced across the surface. In contrast the dry, high-speed diamond grinding wheel retained only a small percentage of the fractured particles and, hence, the

polishing effect was reduced to a minimum.

Representative profiles and C.L.A. values were obtained for each
of these surface finishes. Several (three to five) C.L.A. readings
were made on each surface to obtain reproducible values. A single
surface profile was also made on each surface.

2. Cleaning Technique

Three separate cleaning techniques were used for the majority of
the friction tests. They are referred to as no cleaning, normal clean-
ing, and chemical cleaning. There were a few tests performed on specimens
cleaned with techniques varying slightly from the above mentioned methods.

No cleaning consisted of merely blowing a stream of nitrogen gas
over the surfaces immediately prior to testing. This was done to remove
any dust or other gross particles that might have collected on the surfaces.
No precautions were taken to remove organic or inorganic contaminants
that might have collected on the surfaces. These samples were handled
and exposed to the laboratory atmospheric conditions for several days
before testing.

Normal cleaning consisted of a thorough scrubbing with Lakeseal
laboratory detergent using a nylon brush, followed by a thorough rinse
under hot, running tap water, and finally a rinse with distilled water.
The specimens were then dried in an oven at approximately 110°C for two
hours. The oven was constantly being flushed with a stream of prepuri-
fied nitrogen gas. After drying the specimens were immediately placed
in the direct shear apparatus and the test begun. The cleaned specimens
were carefully kept from coming into contact with any uncleaned objects
prior to testing.

This cleaning procedure is essentially the same as that used by Horn (8) and many other earlier investigators. Bromwell (10) also employed approximately this same procedure for a number of friction tests.

Chemical cleaning makes use of chemical solvents and de-greasers in obtaining a clean surface. This procedure was developed by Bromwell (10). The following sequence is used in the process: (1) trichloroethylene rinse; (2) acetone rinse; (3) detergent wash; (4) distilled water rinse; (5) methyl alcohol rinse; and (6) acetone rinse. The specimens were handled through step 4 with polyethylene gloves. Stainless steel tongs were used thereafter. After step 6 the specimens were immediately placed in the apparatus and the test begun. No drying was necessary as the acetone rapidly evaporates at room temperature.

The miscellaneous cleaning techniques used were primarily variations in the chemical cleaning procedure. Three of these methods consisted of the insertion of an additional step (between steps 3 and 4) in the chemical cleaning procedure. In one case this was a rinse in dilute hydrochloric acid. In another case this was a rinse in hydrogen peroxide. In the third case this was a rinse in dilute hydrosulfuric acid. A fourth technique consisted of a rinse in hot chromic acid for two minutes, a rinse in distilled water, and finally a rinse in acetone. A fifth technique consisted only of an iso-propyl-alcohol vapor rinse for two minutes. In all cases polyethylene gloves or stainless steel tongs were used to handle the specimens.

3. Testing Procedure

After cleaning the specimens were placed in the direct shear apparatus. Each quartz block (top and bottom) was placed in its

respective shear box section using stainless steel tongs. The top block was then placed in contact with the bottom block and the surfaces aligned so that the top block was resting squarely and to the rear of the bottom block (the top block is chamfered 1/16 inch all around). The ball bearing and hanger rig was placed on the top shear box section and the desired normal load stacked on the hanger rig. The strain dial was then placed in contact with the top shear box section and all wire connections were made. The motor was started and the recorder pin set in motion. While the test proceeds, strain dial readings were marked on the recorder chart. The test was stopped by shutting off the motor after several stick-slips have taken place.

If a submerged test was to be made, the surfaces were separated (after the normal load was removed) and the water-tight box filled with the fluid. Distilled water was the only fluid used. The surfaces were then placed back into contact and the test set up and run as before. Many submerged tests were set up by first cleaning the specimens with the desired cleaning procedure and then placing the specimens in the appropriate shear box sections, while the water-tight box was already filled with fluid.

4. Calibration

The transducer and recorder were calibrated each day that tests were run. This was accomplished by hanging the force transducer and a hanger frame vertically and piling dead weights on the hanger frame. The recorder pen deflection was then noted for various loads. A calibration factor was then calculated for use in that day's tests.

There is some frictional resistance in the apparatus due to the interaction of the shaft and the ball bearings. There is also additional

force applied to the top shear box section by the strain dial. The sum of these two factors was calibrated. Two squares of teflon were placed between the top and bottom shear box sections. All the wire connections were made and the strain dial put into contact with the top shear box section. The motor and the recorder were started. A trace was made of the total frictional resistance imparted by the apparatus. The frictional resistance imparted by the apparatus could then be subtracted from the frictional resistance measured during a test, thus giving the frictional resistance of the quartz surfaces.
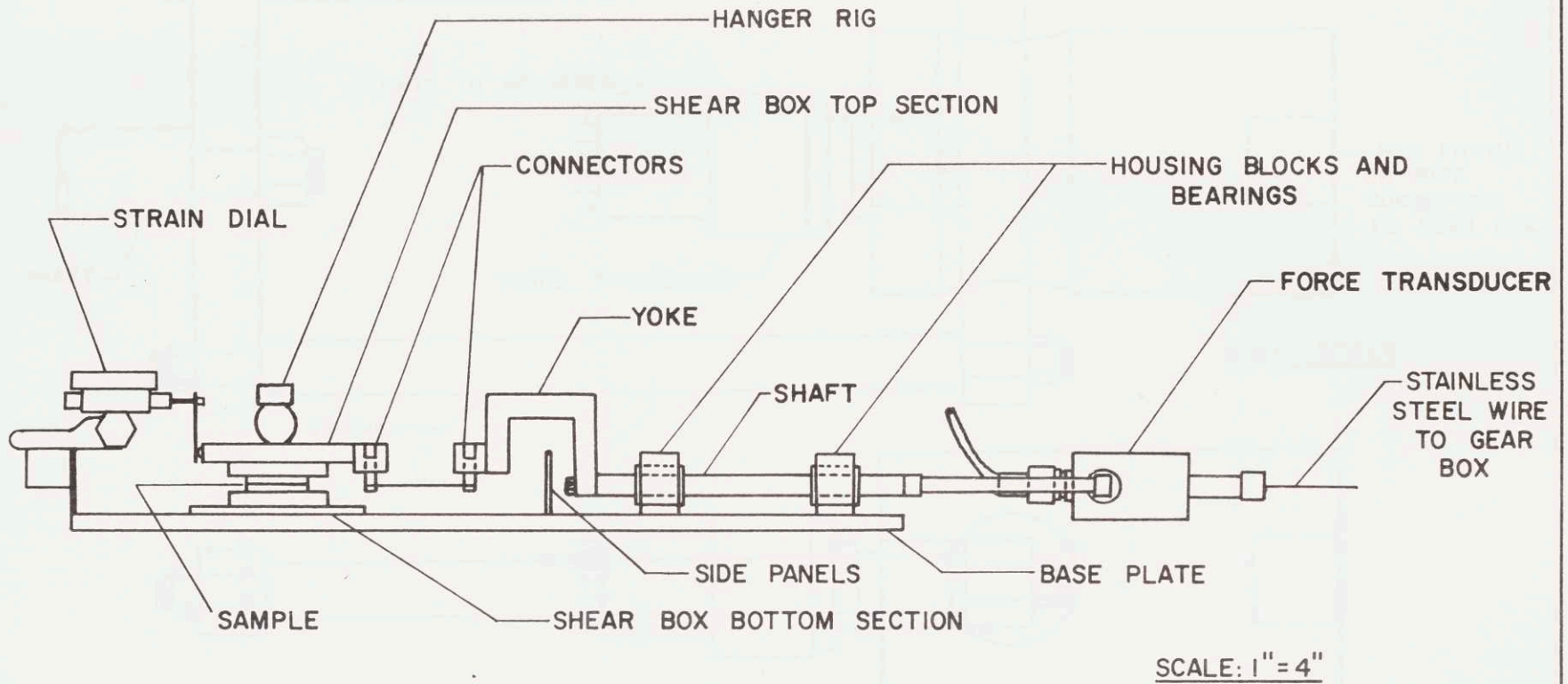
FIGURE 8. DIRECT SHEAR APPARATUS

LEADS TO RECORDER

SHAFT

FORCE TRANSDUCER

FRAME

FOR FITTING
ON WIRE
CONNECTION
TO GEAR BOX

FULL SCALE
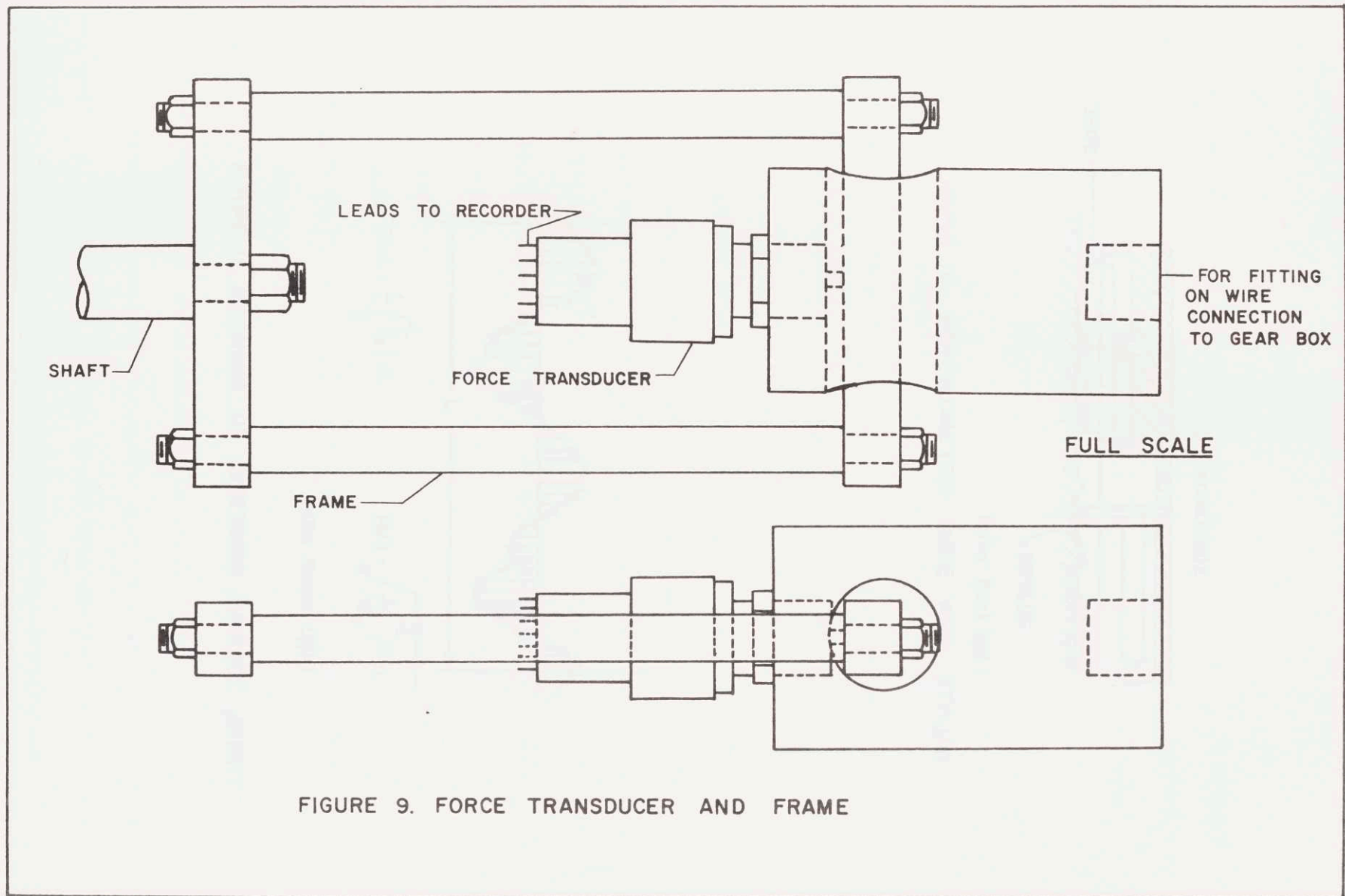
FIGURE 9. FORCE TRANSDUCER AND FRAME

NOSEPIECE
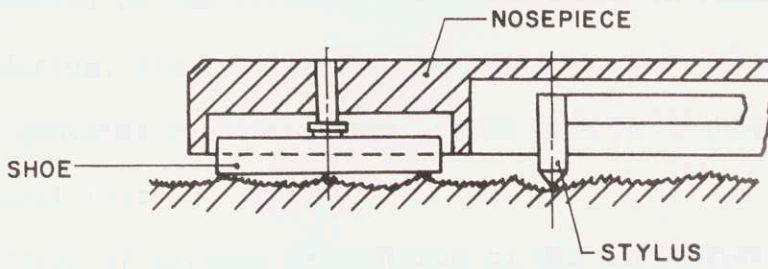
SHOE

STYLUS

(after Rank (12))

FIGURE 10. PROFILOMETER SHOE AND STYLUS

y

L
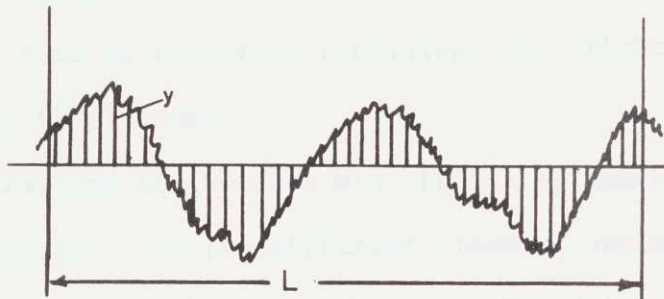
$$CLA = \frac{1}{L}\int_0^L |y|\, dL \qquad\qquad RMS = \sqrt{\frac{1}{L}\int_0^L y^2\, dL}$$

(after Reason (13))

FIGURE 11. METHODS OF ASSESSING AVERAGE HEIGHT

IV. <u>RESULTS</u>

The results of the friction tests are shown in Figures 12 through 25. In addition, the results for all tests are tabulated in Appendix B. Appendix C contains representative traces made by the recorder pen during several tests.

The effect of surface cleanliness on the coefficient of friction is indicated in Figure 12. The horizontal brackets indicate the range of center-line-average values obtained for each particular surface. The vertical brackets indicate the range of friction values obtained if more than one test were run for the particular surface and cleaning procedure. The absence of vertical brackets implies that only one run was made at that set of conditions. In all cases the highest or peak value of friction was plotted. This is further explained in Appendix C. For more than one test at identical conditions the arithmetic average of the peak values is plotted.

Figures 13, 14, and 15 indicate the effects of water on the coefficient of friction for the different cleaning procedures used. There are no range brackets in these figures. The C.L.A. ranges indicated in Figure 12 apply to Figures 13, 14, and 15. Any horizontal ranges indicated in Figure 12 also apply to the corresponding dry test in Figures 13, 14, and 15.

Figure 16 represents the effects of exposure to laboratory atmospheric conditions on the coefficient of friction. Figures 17 and 18 are plots of frictional resistance vs. normal force for smooth and for rough quartz surfaces. Figures 19 through 24 contain the surface traces made with the profilometer and the corresponding center-line-average values for each type of surface used.

Figure 25 is a drawing to equal vertical and horizontal scales of a portion of both a rough and a smooth surface. The peak labeled "A" in Figures 19 and 20 was drawn to scale in Figure 25. These peaks very closely resembled each other in the surface profile.

FIGURE 12. COEFFICIENT OF FRICTION vs. CENTER-LINE-
AVERAGE FOR VARIOUS CLEANING PROCEDURES
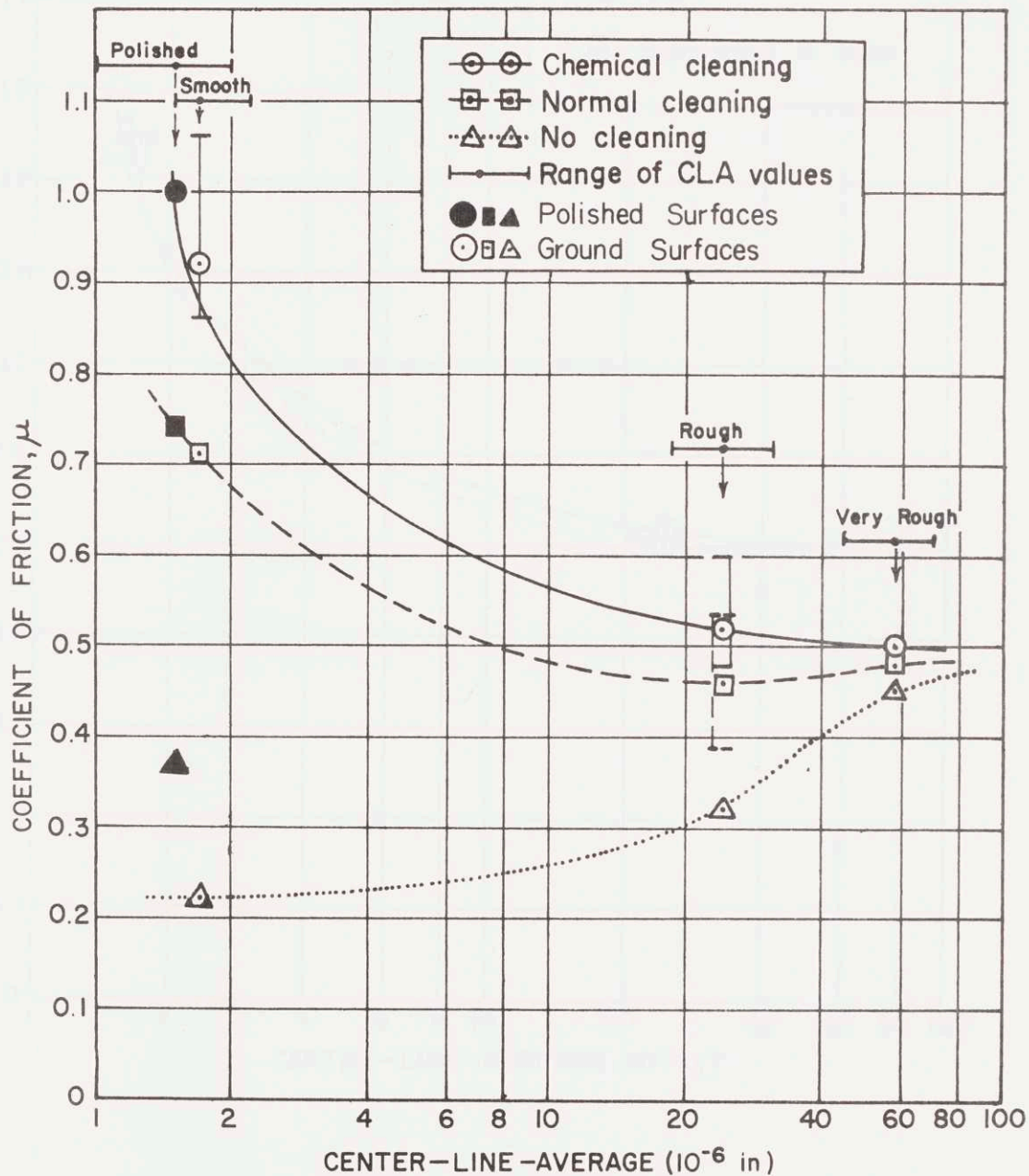
FIGURE 13. COEFFICIENT OF FRICTION vs. CENTER−LINE−
AVERAGE FOR CHEMICAL CLEANING, DRY AND
SUBMERGED.
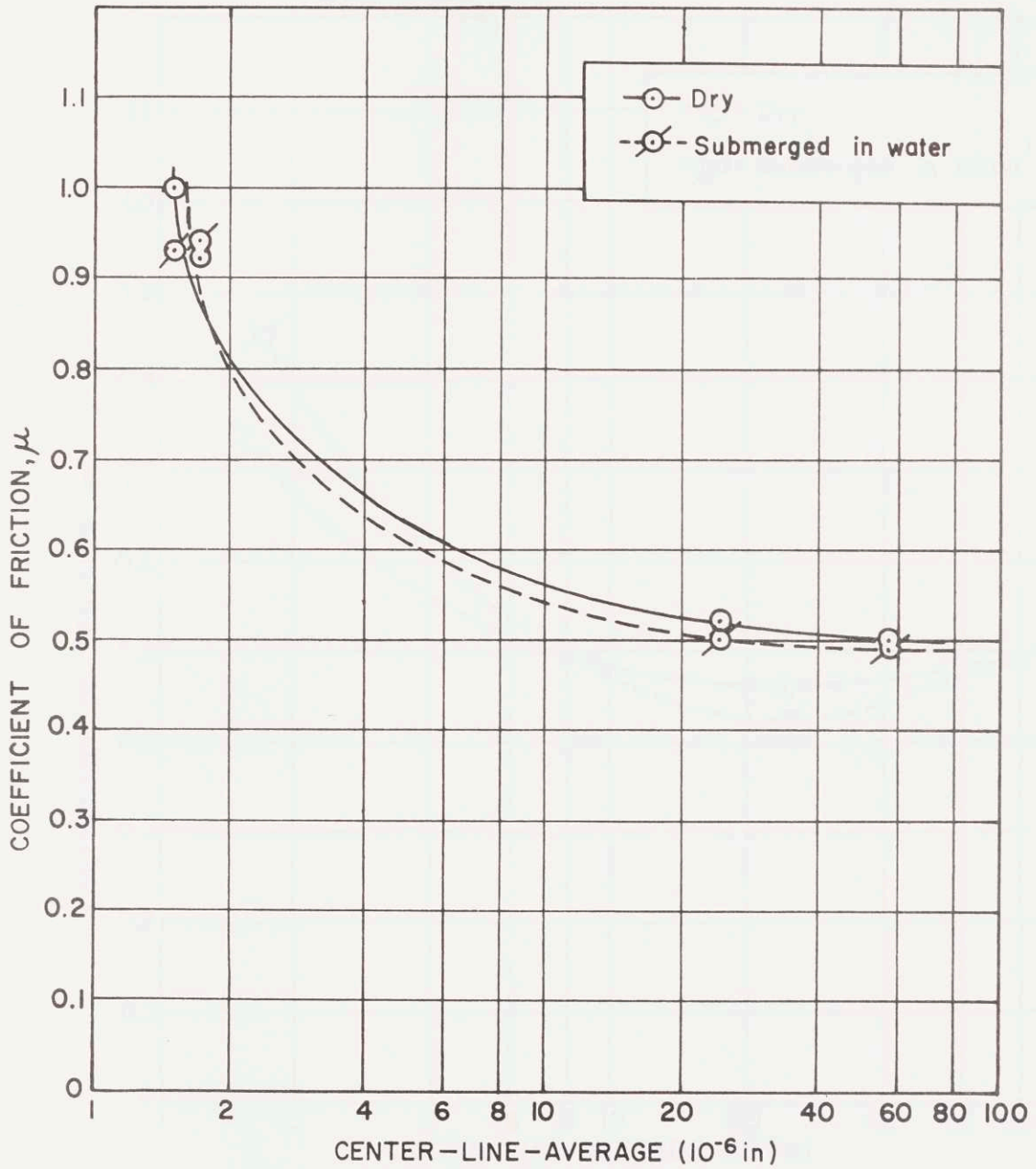
FIGURE 14. COEFFICIENT OF FRICTION vs. CENTER-LINE-AVERAGE FOR NORMAL CLEANING, DRY AND SUBMERGED.
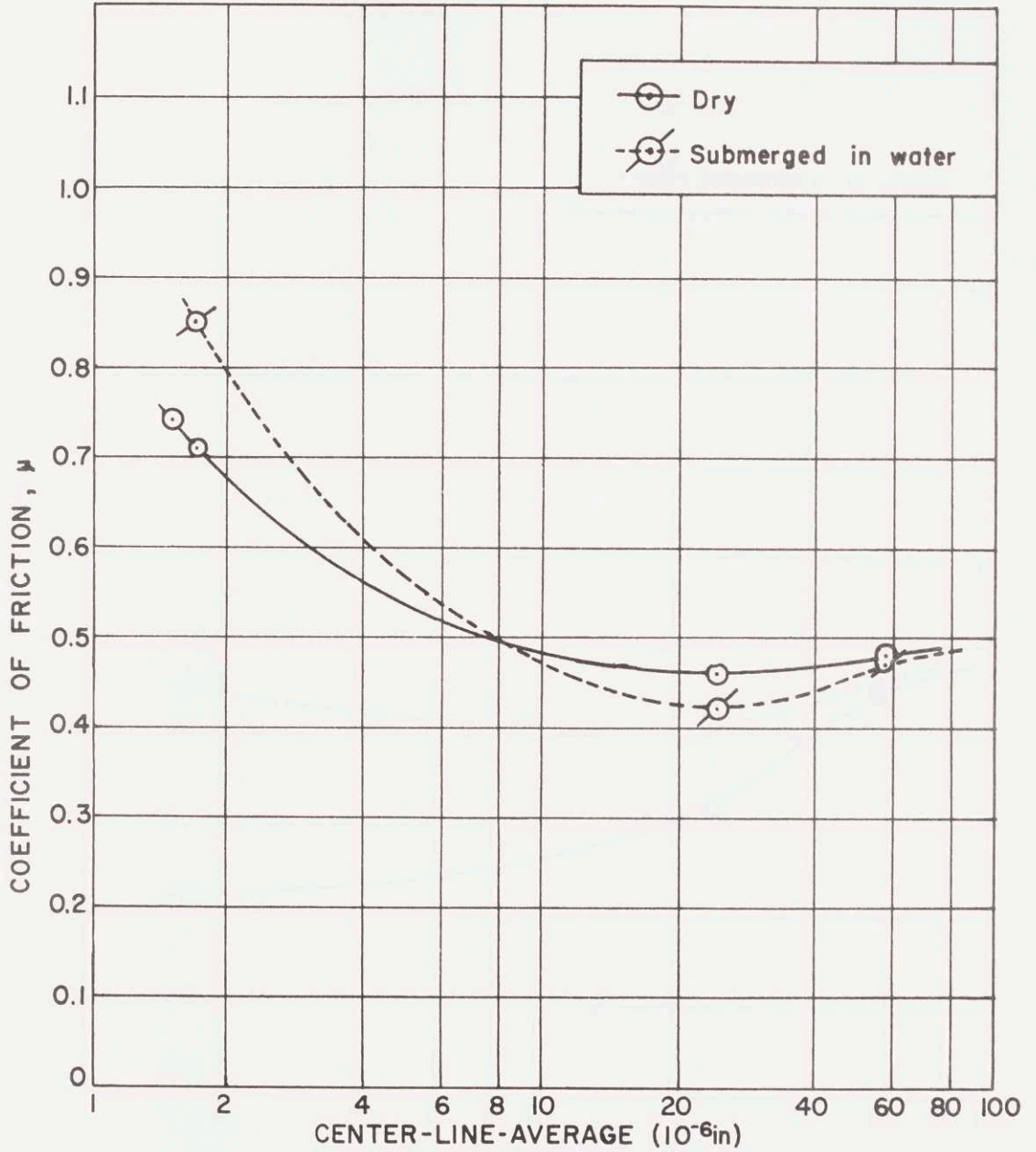
FIGURE 15. COEFFICIENT OF FRICTION vs. CENTER-LINE-AVERAGE FOR NO CLEANING, DRY AND SUBMERGED.
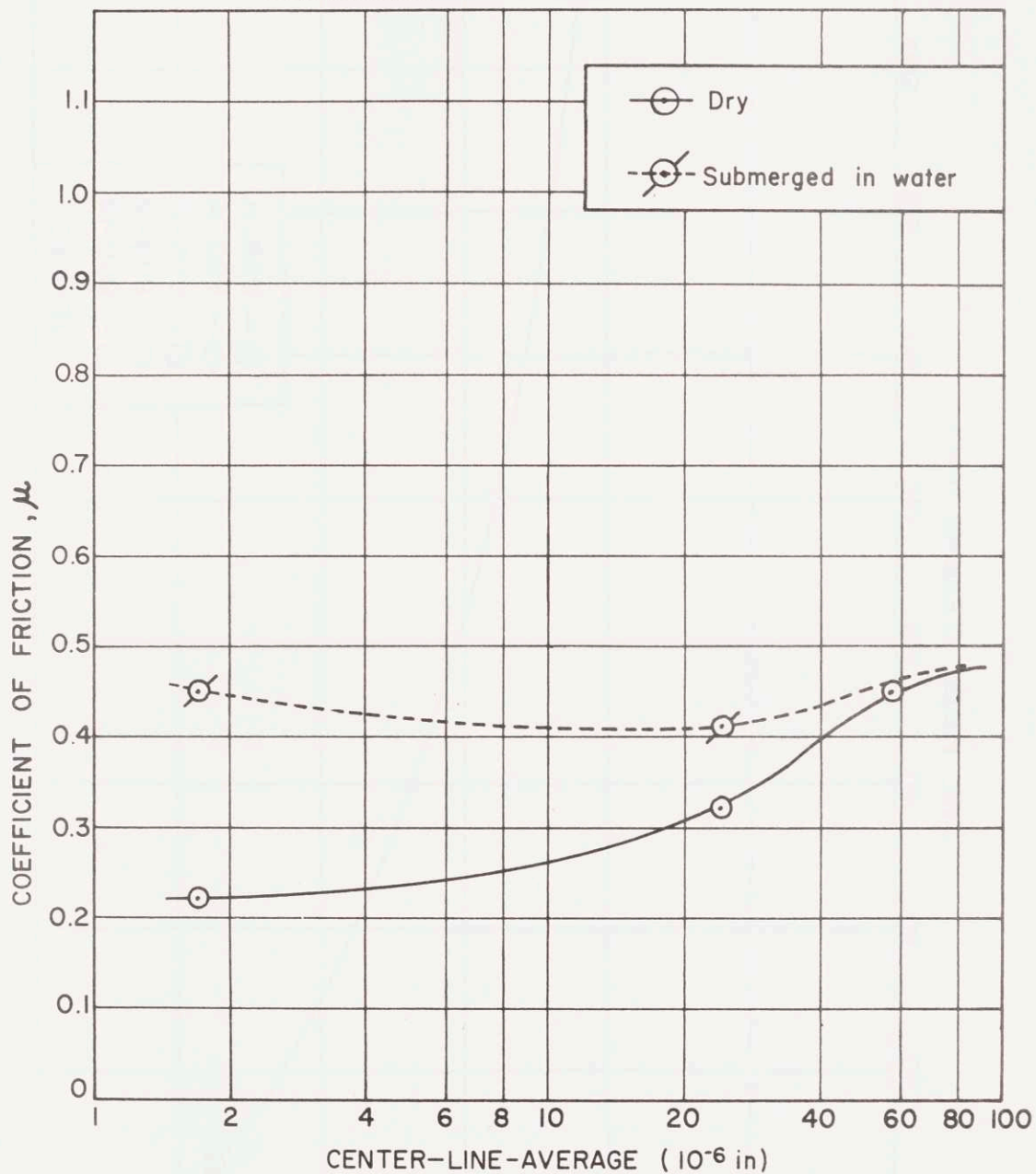
FIGURE 16. COEFFICIENT OF FRICTION vs. TIME ELAPSED AFTER CHEMICAL CLEANING
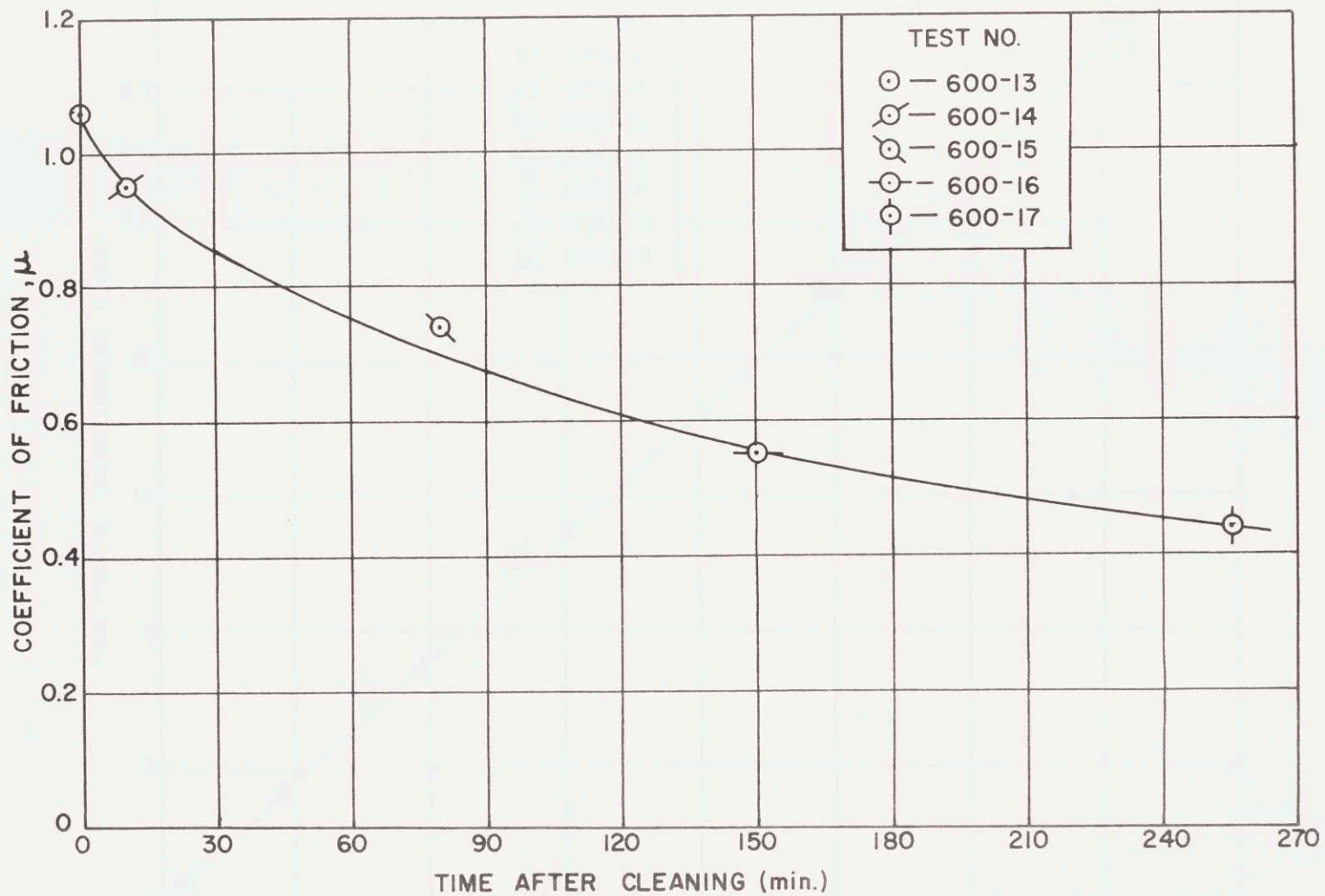
FIGURE 17. FRICTIONAL RESISTANCE vs. NORMAL FORCE FOR SMOOTH QUARTZ

CHEMICALLY CLEANED SURFACES
TEST NO.
⊙ 600-3
⊘ 600-4
⊙ 600-5
⊖ 600-6
⊙ 600-7
⊕ 600-13
⊗ 600-18

$\phi_\mu = 42°$

FRICTIONAL RESISTANCE, T (kg)
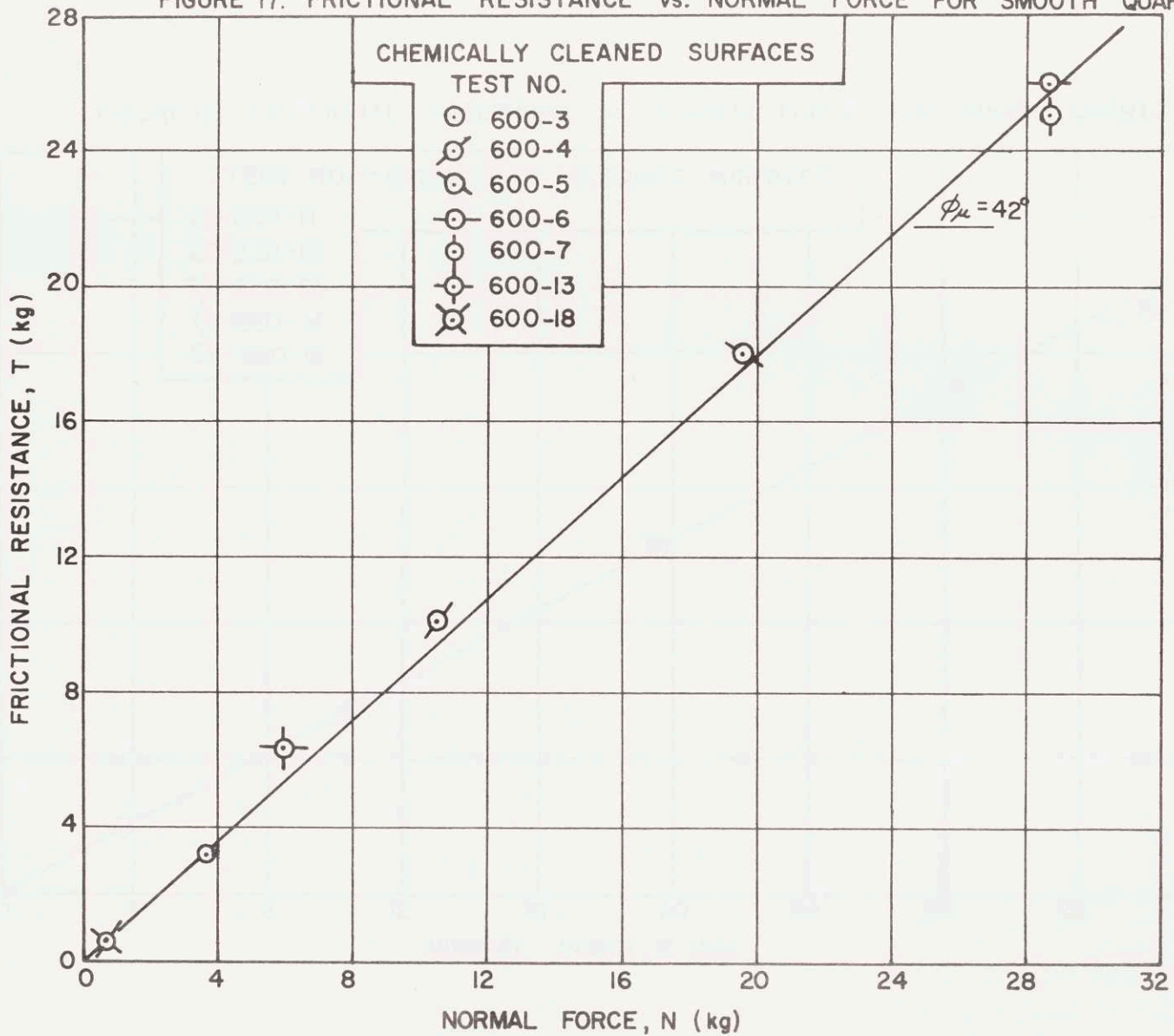
NORMAL FORCE, N (kg)

FIGURE 18. FRICTIONAL RESISTANCE vs. NORMAL FORCE FOR ROUGH QUARTZ
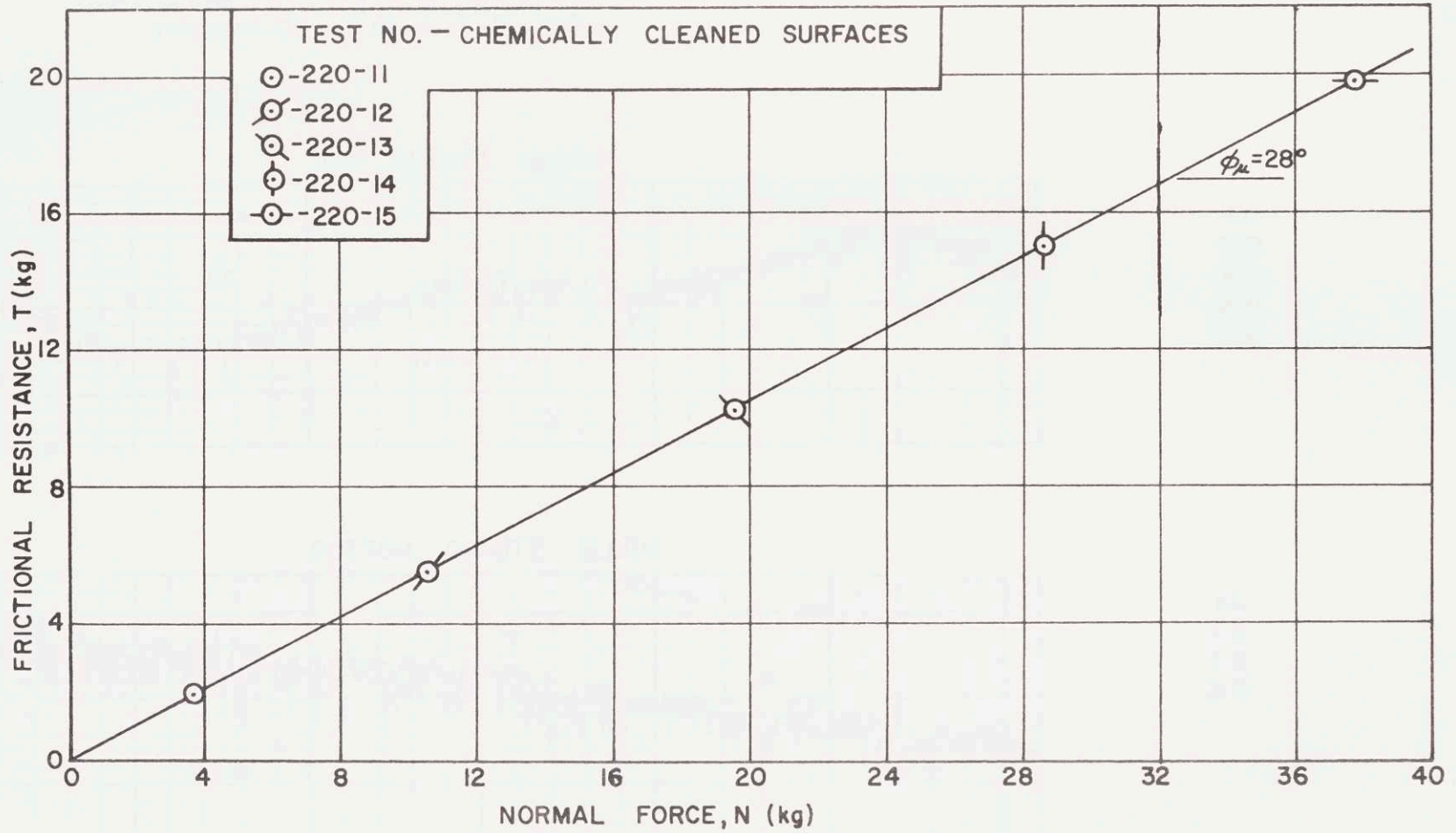
FIGURE 19. SURFACE ROUGHNESS OF SMOOTH QUARTZ

a. SURFACE TRACES

Scale: vertical – 0.1 in.(1 division) = 2×10^{-6} in.
horizontal – 0.2 in.(1 division) = 2×10^{-3} in.

b. CENTER-LINE-AVERAGE
VALUES (10^{-6} in.)

TOP QUARTZ BLOCK

air
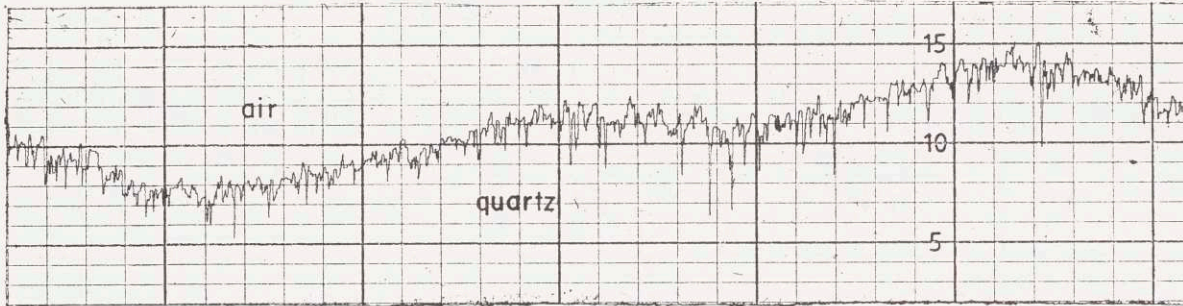
quartz

1.0
2.0
2.0
2.0
2.2

BOTTOM QUARTZ BLOCK

air
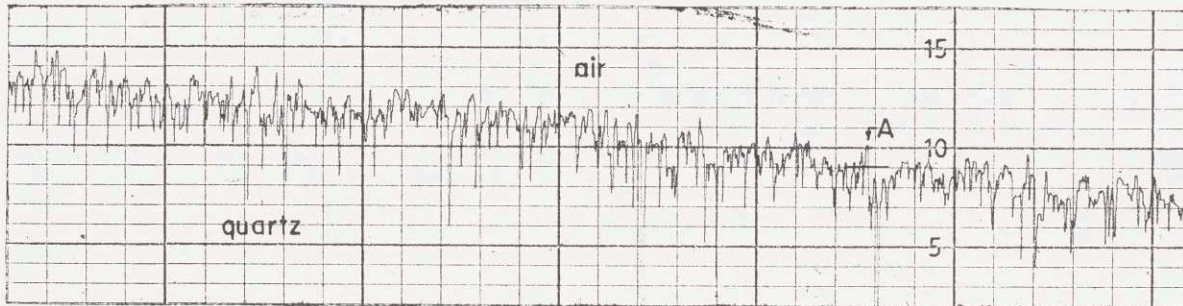
quartz

1.5
1.5
1.5
2.0

FIGURE 20. SURFACE ROUGHNESS OF ROUGH QUARTZ

a. SURFACE TRACES

Scale: vertical – 0.1 in. (1 division) = 2×10^{-5} in.
horizontal – 0.2 in. (1 division) = 2×10^{-3} in.

b. CENTER–LINE–AVERAGE
VALUES (10^{-6} in.)
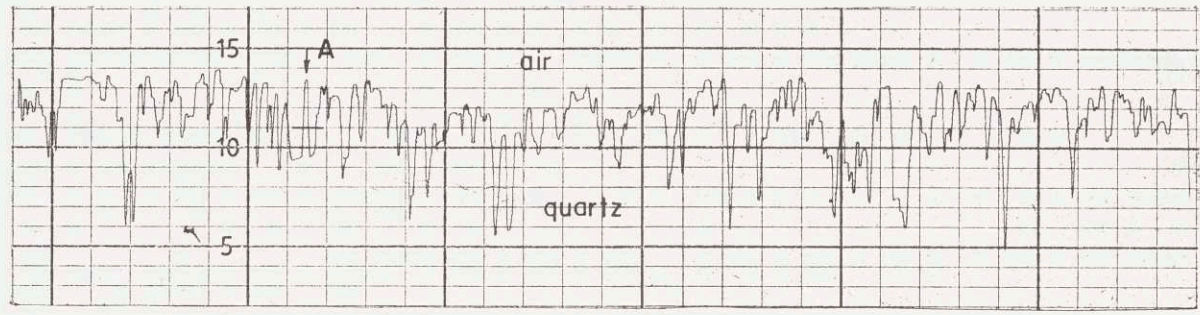
TOP QUARTZ BLOCK

22
20
19.5
25

BOTTOM QUARTZ BLOCK

26
22
30.5
18.5
31

FIGURE 21. SURFACE ROUGHNESS OF VERY ROUGH QUARTZ

a. SURFACE TRACES

b. CENTER-LINE-AVEAGE
VALUES (10⁻⁶ in.)

Scale: vertical− 0.1 in. (1 division) = 5 x 10⁻⁵ in.
horizontal− 0.2 in. (1 division) = 2 x 10⁻³ in.
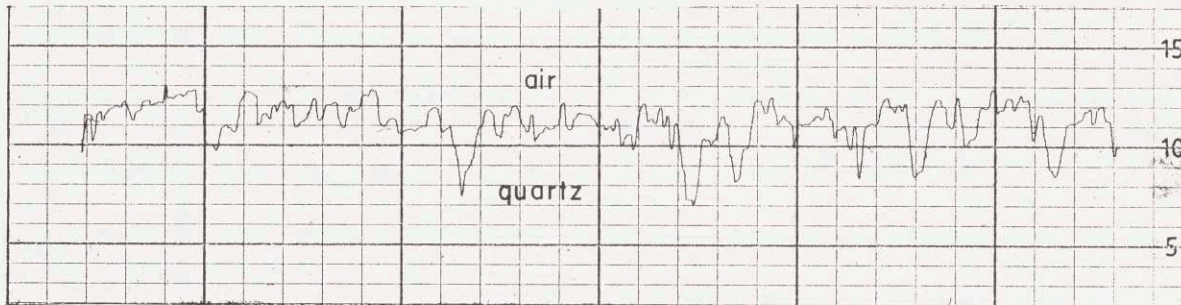
TOP QUARTZ BLOCK

60
50
50
70

BOTTOM QUARTZ BLOCK
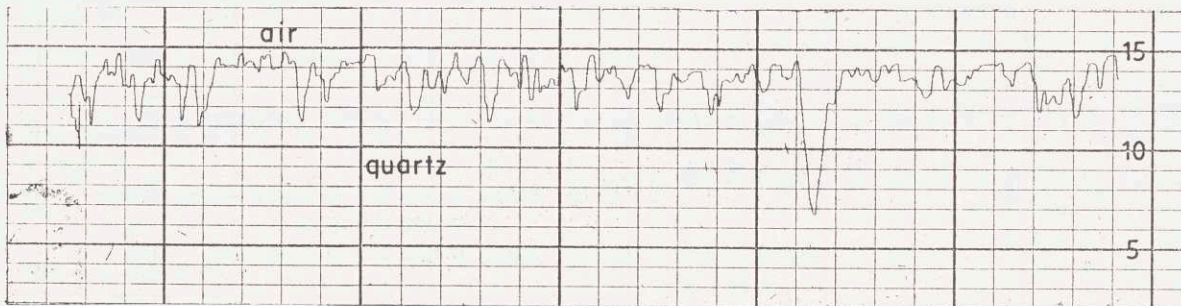
70
44
48
64

FIGURE 22. SURFACE ROUGHNESS OF POLISHED QUARTZ

a. SURFACE TRACES

Scale: horizontal - 0.2 in. (1 division) = 2×10^{-3} in.

TOP QUARTZ BLOCK —— vertical - 0.1 in.(1 division) = 2×10^{-6} in.

b. CENTER-LINE-AVERAGE
VALUES (10^{-6} in.)
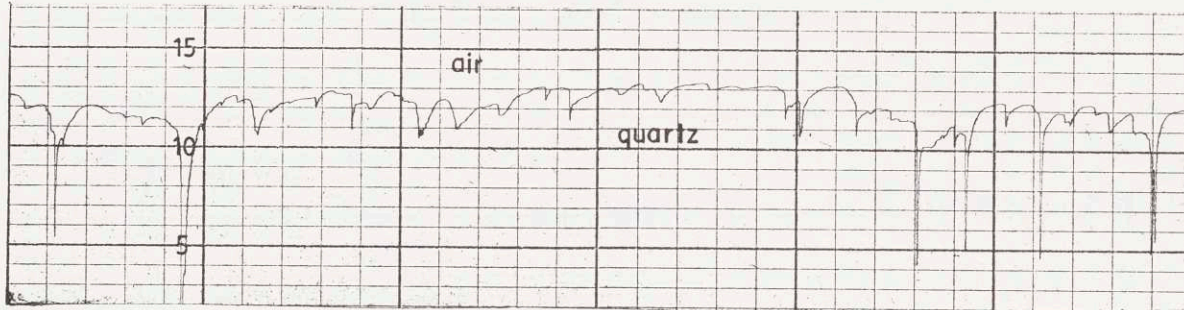
2.0
1.0
1.2
1.8

BOTTOM QUARTZ BLOCK — vertical - 0.1 in.(1 division) = 1×10^{-5} in.
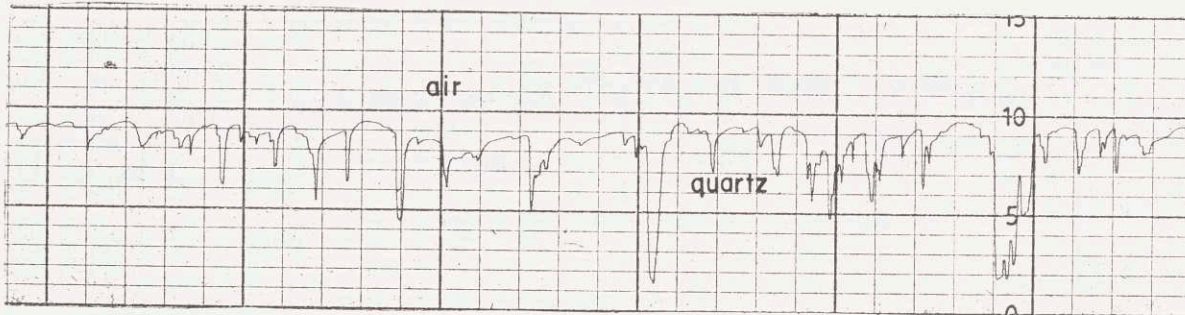
8
12
11
7

FIGURE 23. SURFACE ROUGHNESS OF HAND-GROUND SMOOTH QUARTZ

a. SURFACE TRACES

b. CENTER-LINE-AVERAGE VALUES (10^{-6} in.)

Scale: vertical – 0.1 in. (1 division) = 2×10^{-6} in.
horizontal – 0.2 in. (1 division) = 2×10^{-3} in.

TOP QUARTZ BLOCK

air
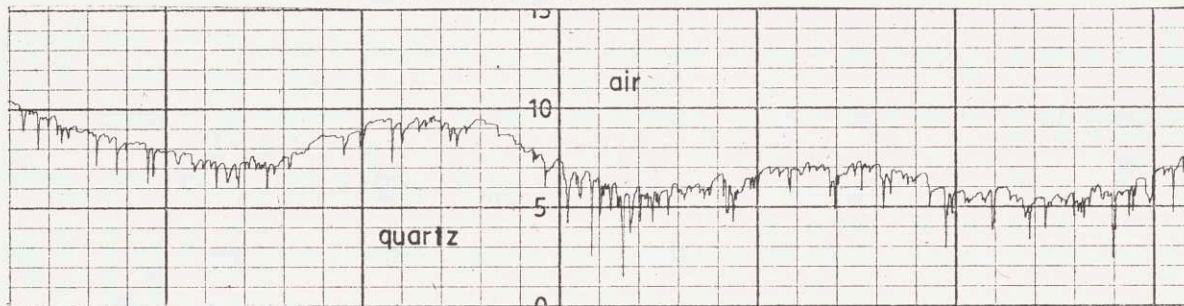
quartz

2.0
3.0
2.2
1.6

BOTTOM QUARTZ BLOCK

air
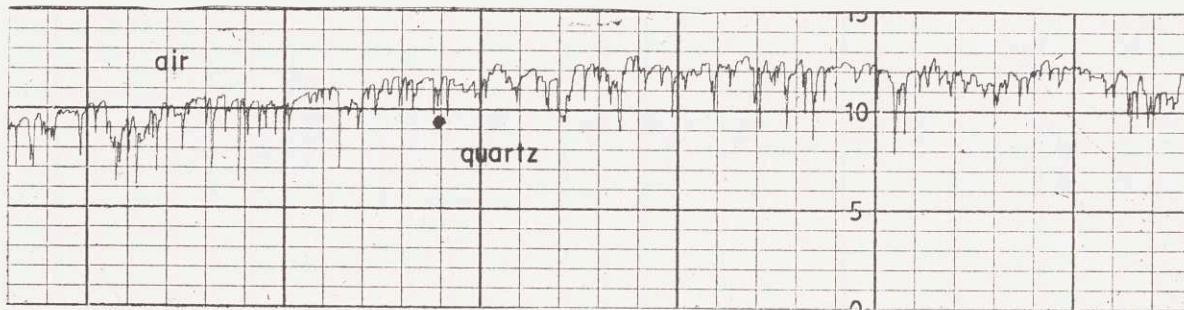
quartz

1.0
1.8
1.2

FIGURE 24. SURFACE ROUGHNESS OF HAND-GROUND ROUGH QUARTZ

a.SURFACE TRACES

Scale: vertical - 0.1 in. (1 division) = 2×10^{-5} in.

horizontal - 0.2 in. (1 division) = 2×10^{-6} in.

b. CENTER-LINE-AVERAGE VALUES (10^{-6} in.)

TOP QUARTZ BLOCK

air
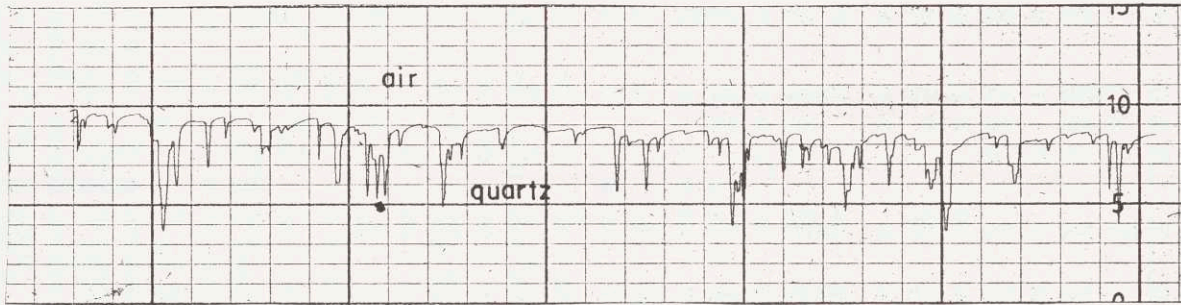
quartz

12
14
16

BOTTOM QUARTZ BLOCK

air
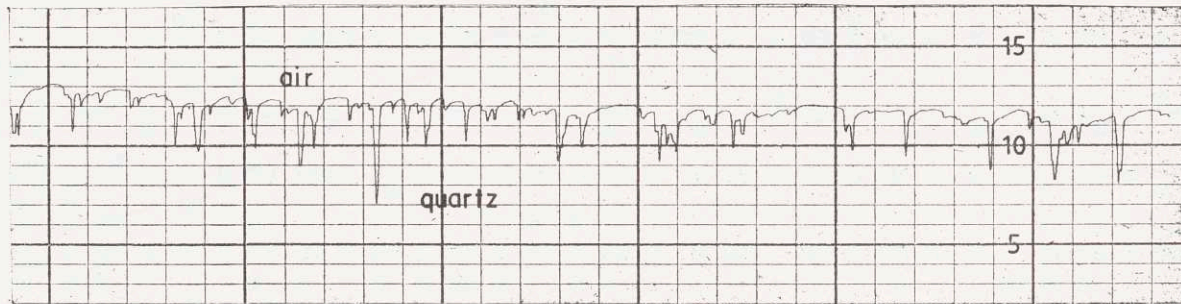
quartz

12
12
14

FIGURE 25. SURFACE ROUGHNESS OF SMOOTH AND ROUGH QUARTZ SURFACES, EQUAL HORIZONTAL AND VERTICAL SCALES

SCALE: 1 in. = 4 x 10^{-5} in.

SMOOTH QUARTZ

BASE LINE IN FIGURE 19

177°

ROUGH QUARTZ

120°

BASE LINE IN FIGURE 20
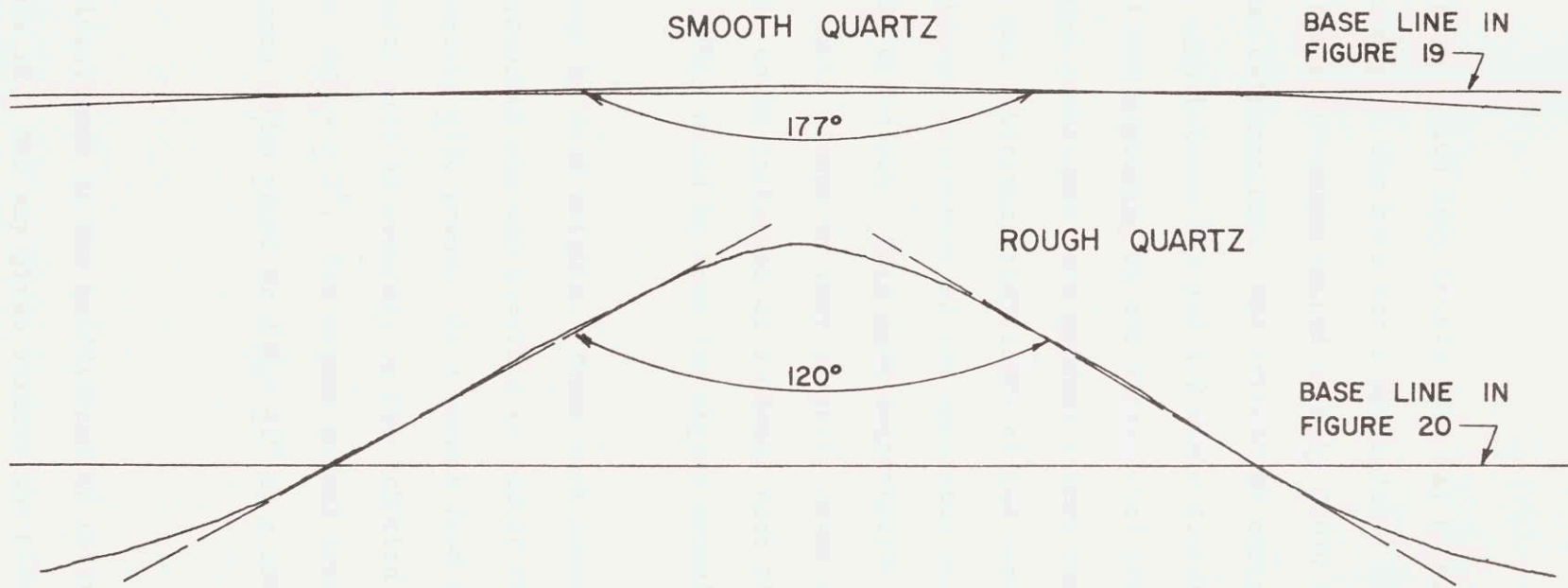
V. DISCUSSION OF RESULTS

A. Accuracy

The recorder pen calibration varied very little from day to day.
The maximum variation from one day to the next was 0.010 kg/cm. Over
the entire period of testing the calibration varied by only 0.030 kg/cm
from the minimum to the maximum calibrations. The frictional resistance
of the apparatus was found to vary between 0.5 and 1.0 scale divisions
(one scale division equals 0.1 cm) depending on the strain dial position.
Any variations in the frictional resistance were gradual (there were
no sharp or sudden changes in the frictional resistance of the appar-
atus). In all tests the frictional resistance of the apparatus was
taken at a maximum or 1.0 scale divisions. This gave conservative
results as the friction value would always be very slightly lower than
actual. The maximum error this could introduce at a normal load of
3.67 kg would be $\Delta\mu = +0.01$. This would be less for higher normal
loads.

The normal load was applied by dead weights. These were accurate
to at least $\pm$ 50 grams. The recorder pen was accurate to better than
1.0 scale division or approximately ± 130 grams. At a normal load of
3.67 kg these conservative limits give an accuracy on the friction
measurments of $\Delta\mu = \pm 0.04$ or $\Delta\phi_\mu = \pm 2^{\circ}$. For higher normal loads
the measurments are more accurate ($\Delta\mu = \pm 0.02$ or $\Delta\phi_\mu = \pm 1^{\circ}$ at a normal
load of 10.48 kg).

B. Surface Cleanliness

The effects of surface cleanliness on the coefficient of friction
are clearly indicated in Figure 12. For any given surface the effect
of cleaning is to increase the value of friction. The effect is much

greater for smooth surfaces than for rough surfaces. With no cleaning the smooth surfaces gave values of $\mu = 0.22$ ($\phi_\mu = 12^o$), while for chemical cleaning these same surfaces gave values of $\mu = 0.90$ ($\phi_\mu = 42^o$). On the other hand, the friction values for rough surfaces increased from $\mu = 0.32$ ($\phi_\mu = 18^o$) with no cleaning to $\mu = 0.52$ ($\phi_\mu = 27^o$) with chemical cleaning. For very rough surfaces the increase was from $\mu = 0.45$ ($\phi_\mu = 24^o$) with no cleaning to $\mu = 0.50$ ($\phi_\mu = 27^o$) with chemical cleaning.

For dirty or contaminated surfaces the friction value increases with increasing roughness. This agrees very well with those ideas presented in the Introduction. Rough surfaces, or rather surfaces with steeper asperities, should require more tangential force during shear in order to pull the top surface up and over the asperities of the bottom surface (Figure 4). The role of surface contaminants would further accentuate this trend of increasing friction with increasing roughness. The steeper (120°, Figure 25) asperities on rough surfaces would more easily "punch" through contaminating surface layers, thereby giving mineral-to-mineral friction. The flatter (175°, Figure 25) asperities on the smooth surfaces would have a more difficult time "punching" through a contaminating layer as the same total normal force would be spread over a larger area. This would imply two possible circumstances for the smooth surfaces: first, there might be less actual mineral-to-mineral contact and more mineral-to-contaminant-to-mineral contact; and second, there would be more contaminants caught in the zone of plastic flow (Figure 3) as the asperities deform.

This explanation does not imply that there is more actual contact area for the case of smooth surfaces. It does imply that there are

fewer asperities coming into contact for the case of rough surfaces; but, that these asperities plastically deform more for the same normal load than the asperities coming into contact for the case of smooth surfaces. The net result is that for the same normal load the actual area of contact is the same for both smooth and rough (or very rough) surfaces.

For cleaned surfaces (both chemical and normal cleaning) the friction value decreases with increasing roughness. This is not the result to be expected. Even presuming that there are no contaminants on the surfaces, the effect of steeper asperities should act to increase the frictional resistance with increasing surface roughness.

This behavior has two possible explanations: first, the rougher surfaces were not as clean as the smooth surfaces (even after subjected to the same cleaning procedure); and second, the actual area of contact for the smooth surfaces was greater than for the rougher surfaces. The second explanation does not appear to be valid. A larger contact area for the smooth quartz would imply that these surfaces were behaving elastically rather than plastically, as both smooth and rough surfaces were subjected to the same normal load. By increasing the normal load, a plot of frictional resistance, T, vs. normal force, N, should result in a curved line (see Eq. 8). As can be seen in Figures 17 and 18 (discussed later) the curves are probably straight lines, indicating no dependence of μ on normal load. This implies that for the same normal load, the actual contact areas are essentially the same for both smooth and rough surfaces. The deviation from a straight line in Figure 17, suggests that a curved line (concave downward) might be drawn through these points. However, what is considered a reasonable

explanation for these deviations is presented later (V. E. Normal Load).

The possibility that the rougher surfaces were not as clean as the smooth surfaces appears to be the best explanation for the great difference in friction values. For this to be the case there must be some reason for the apparent inability of removing the surface contaminants. One possibility is that there are cracks and fissures of molecular dimensions on the rougher surfaces which do not exist on the smooth surfaces (or which exist with much less frequency). These features would be too small to be detected by the profilometer. Contaminating molecules could find their way into these cracks and fissures and become chemically adsorbed to the quartz from two or three directions. The contaminating molecules would then be extremely hard to remove by cleaning processes. These cracks and fissures must originate as a result of large surface stresses induced by the fracture of a piece of quartz by the grinding wheel. The larger fractures produced by the rougher grinding wheel induces larger surface stresses and hence more cracks and fissures on the surface.

Variations in cleaning technique were made on the rough surface in an attempt to raise the friction value. These results can be seen in Appendix B, Table II, Test Nos. 220-3 through 220-11. These methods had very little effect in raising the friction value. This would seem to indicate that if the rough surfaces are not being cleaned, the contaminants are strongly attracted to the quartz surface or are in inaccessible places.

As the surfaces became very rough (Figure 12), the value of friction reached an asymptotic value of $\mu = 0.49$ ($\phi_\mu = 26°$). Cleaning has very little effect on these very rough surfaces. This value of $\phi_\mu = 26°$

agrees very well with Rowe (1) who reported $\phi_\mu = 26° \pm 4°$, for quartz soil particles depending on the grain size.

Horn (8) reported a value of $\phi_\mu = 28°$ for rough surfaces. These surfaces were ground with a 240 grit material. This would correspond to a C.L.A. value of approximately 14×10^{-6} in. (Figure 24). Referring again to Figure 12, this would give a value of $\mu = 0.46$ or $\phi_\mu = 25°$ for normally cleaned surfaces.

Figure 16 indicates the effect of exposure to the laboratory atmosphere on the coefficient of friction. The room temperature at the time of exposure was about 24°C. The curve shows a fairly gradual decrease in friction with time. Bromwell (10) reported a decrease of 35% in friction from $\mu = 0.73$ to $\mu = 0.46$ when a chemically cleaned sample was subjected to 110°C. for 15 minutes after cleaning. Figure 16 indicates that a corresponding decrease of 35% from $\mu = 1.06$ to $\mu = 0.69$ takes approximately 85 minutes (a decrease from $\mu = 0.73$ to $\mu = 0.46$ in Figure 16 takes approximately 170 minutes). This would indicate that high temperatures may increase the rate of contamination of clean quartz surfaces.

Further investigation of this phenomenon is required to substant-iate the effects of time and high temperatures on the contamination of quartz and mineral surfaces. High temperatures and long drying times in sample cleaning and preparation may be partially responsible for the low values of friction for quartz reported by many investigators.

The values of friction reported in this investigation for smooth surfaces are higher than any values found in the literature to date. This is, however, no indication that the highest value ($\mu = 1.06$) reported is yet the maximum value of friction obtainable for quartz.

Higher friction values may eventually be produced with more effective cleaning techniques or with smoother surfaces.

C. Surface Roughness

Traces made by the profilometer on each of the six surface finishes used in the investigation are shown in Figures 19 through 24. These traces and the center-line-average values gave a good comparison of the relative roughnesses of the different surfaces. The smooth and rough surfaces differ in roughness by approximately one order of magnitude. The rough and very rough surfaces differ by a little more than a factor of two. The surface traces depict the asperities as being rather sharp with narrow valleys between asperities. However, it must be noted that the horizontal scale is compressed two or three orders of magnitude (depending on the surface) with respect to the vertical scale. The scale drawing of Figure 25 indicates that the asperities, even of rough surfaces, are very smoothed. This smoothness, however, is probably due to the large size of the diamond tip in relation to the asperity size. Small surface irregularities (of molecular dimensions) are impossible to detect.

The traces on smooth, rough, and very rough surfaces (Figures 19, 20, and 21) show the same general characteristics, i.e. sharp, narrow asperities. The polished surface traces (Figure 22) show wide, well rounded asperities. The difference between the ground and the polished surfaces is very evident. The two surfaces wet-ground by hand with carborundum paper (Figures 23 and 24) show characteristics intermediate between those surfaces ground with the diamond dust wheels and the polished surface. The asperities are fairly narrow, but the tops appear to be rounded off.

The polished surfaces were originally prepared by rubbing the two blocks together with a paste of jeweler's rouge and water between the surfaces. After a long period of polishing, the surfaces had a distinct reddish color. This color could not be removed by any of the cleaning processes employed in this investigation. This led to the conclusion that the jeweler's rouge had been forced into the quartz matrix during polishing, distorting the original matrix and forming a "fudge" of quartz and jeweler's rouge close to the surface. These surfaces were then polished using an aluminum oxide suspension and a polishing wheel as described in Section III. It was assumed that this polishing action also produced a "fudge" on the surface, this time of aluminum oxide and quartz.

The two samples wet-ground on carborundum paper were also considered to have surfaces at least partially covered with a "fudge" of grinding material and quartz. As seen in Tables V and VI in Appendix B, these surfaces did not give friction values corresponding to their surface roughness as indicated by Figure 12. The friction values were, however, very close to those obtained with polished surfaces.

The three diamond-wheel ground samples probably had surfaces in which the silicon-oxygen arrangement was typical of the quartz crystalline matrix (Figure 6a). However, the freshly broken or fractured surfaces quickly became contaminated. The polished and very likely the wet-ground samples had surfaces in which the silicon-oxygen arrangement had been substantially disturbed. An amorphous layer of silicon, oxygen, and metallic grinding material probably formed over this disturbed layer (6). The polished and wet-ground sample tests were not measuring the friction of the quartz crystalline matrix, but of the amorphous layer

of silicon, oxygen, and metallic grinding material. Thus, the tests run on these two distinct types of surfaces could not realistically be compared. Actually, the polished and wet-ground surfaces were not measuring the friction of quartz, but the friction of a "fudge" of both metal and mineral.

The effects of surface roughness cannot be separated from the effects of surface cleanliness. As discussed in the previous section, rough surfaces have higher friction values than smooth surfaces when both are dirty, but lower values when both are cleaned. This is not what would normally be expected. This effect is apparently due to the inability of getting the rough surfaces as clean as the smooth surfaces. Until methods of actually determining the degree of surface cleanliness are developed, the effect of surface roughness alone cannot accurately be studied.

D. Effect of Water

Water has a very small affect on the friction of chemically cleaned surfaces, as shown in Figure 13. For dirty surfaces water has a noticable effect in increasing the friction (Figure 15). With normally cleaned surfaces the effect of water is not so obvious (Figure 14). Friction increases on smooth surfaces and apparently decreases on rough surfaces with the addition of water.

The effect of water is to disrupt an adsorbed surface contaminating layer, reducing its effectiveness as a lubricant. This is very likley the case for dirty surfaces. Any contaminants that have remained on the chemically cleaned surfaces are apparently not effected by water. This would be the case if the remaining contaminants were strongly attracted to the quartz surface.

For the rough and very rough surfaces water apparently has very little effect on the measured friction value of normally and chemically cleaned surfaces. For these surfaces any remaining contaminants are probably inaccessible or are so strongly attracted to the quartz surface that the water has very little effect in disturbing the contaminating layer.

E. Normal Load

Changes in normal load produced no noticable effect on the value of friction for any particular sample. Figures 17 and 18 are plots of frictional resistance vs. normal load. This line is probably straight for both smooth and rough quartz. If the quartz was behaving elastically, these lines should be curved.

The plot for rough quartz (Figure 18) indicates that there is little or no variation from a straight line. On the other hand, the plot for smooth quartz (Figure 17) indicates that there is a significant amount of scatter from the straight line. There are two explanations for this: first, minor differences in surface cleanliness have a much larger effect on friction for smooth surfaces than for rough surfaces; and second, all the points shown for the rough quartz were obtained on the same specimen, while three specimens were used in obtaining the points shown for the smooth quartz. The first explanation has already been discussed in detail.

The fact that each time a surface was reground it exhibited its own unique frictional characteristics for the same cleaning conditions is illustrated in Figure 17. The tests that were run on the same surface show almost identical friction values (such as test nos. 600-13 and 600-18). This fact is also exhibited for rough quartz (compare test nos. 220-15 through 220-19 with test no. 220-2 for example). This

implies that there is no unique value of friction for quartz, especially in nature where each quartz sand grain or quartz rock will possess slightly defferent surface characteristics. Extremely small variations in surface roughness (smaller than could be measured with the available equipment) produce noticable effects on friction for clean surfaces. A better statement might possible be that small variations in surface roughness produce variations in surface cleanability.

F. Multiple Testing of the Same Surface

As upper limit was arbitrarily set at six or seven tests on each surface before it was reground. This was to prevent the surfaces from becoming significantly deformed and giving erroneous test results. Any surfaces that exhibited visible wear after a test were reground before subsequent use.

One test (No. 220-13) was run on a sample of rough quartz which exhibited visible wear. This test gave a value of friction of $\mu = 0.6c$ which is considerably higher than any other value for rough quartz. The surfaces obviously had been deformed in previous tests, resulting in either a smoother (more polished) surface or a surface containing wear tracks. Both types of deformation would give a higher friction value.

VI. CONCLUSIONS

1. The degree of surface cleanliness is the major factor influencing
    the coefficient of friction of quartz. By changing the cleaning
    technique the friction value can be increased or decreased.

2. The effects of surface roughness alone on the coefficient of
    friction cannot be studied independently of the degree of surface
    cleanliness. Apparently, the surface roughness strongly affects
    the cleanability of quartz surfaces. Smooth surfaces are more
    easily cleaned than rough surfaces. The result is considerably
    higher values of friction for chemically and normally cleaned
    smooth surfaces than for rough surfaces.

3. With increasing surface roughness, the range of friction values
    obtainable with varying surface cleanliness decreases significantly.
    Quartz soil particles will have rough surfaces, therefore reducing
    the error in estimating ϕ_μ. The range of friction angles for
    rough surfaces agree very well with the values $\phi_\mu = 26^\circ \pm 4^\circ$
    reported by Rowe ($\underline{1}$) for quartz soil particles.

4. Water acts as a anti-lubricating agent for dirty quartz surfaces
    or partially cleaned smooth quartz surfaces. The effect of water
    is not so obvious for very clean smooth surfaces and partially
    cleaned rough surfaces. This is apparently due to the inaccessi-
    bility of the contaminating molecules or a strong attraction between
    these molecules and the quartz surface.

5. Very high values of friction may be obtained on clean, smooth
    quartz surfaces. There is no indication that the highest value
    obtained in the investigation (μ = 1.06) is yet the highest

friction value obtainable for crystalline quartz surfaces.

6. The coefficient of friction decreases with an increase in the time of exposure to atmospheric conditions for chemically cleaned smooth quartz surfaces. This is due to progressive contamination of the surface. High temperatures may tend to increase the rate of contamination.

VII. <u>RECOMMENDATIONS</u>

1. Either a method of determining the degree of surface cleanliness
    or a method of getting a truly clean surface must be developed
    before other individual effects, such as surface roughness, may
    be studied with any degree of confidence in the results.

2. The effects of fluids other than water on the friction of quartz
    have been studied and reported by several investigators. An
    investigation using other fluids and the improved cleaning tech-
    niques might lead to a further knowledge of the surface conditions
    and frictional properties of quartz.

3. The effects of high temperatures on the rate of progressive contam-
    ination of clean quartz surfaces bears further investigation. This
    way also lead to an increased understanding of the surface conditions
    and surface properties of quartz.

VIII. APPENDICES

A. Details of Apparatus

A Marathon Electric model No. YJ 161E36 W, ¼ Hp constant speed
motor was used. It was attached to a Graham variable speed trans-
mission. This was connected by a flexible cable to two Boston Gear
gear boxes in series. The first box had a 45:1 reduction and the
second second had a 20:1 reduction, for a total gear reduction of
900:1 from the transmission.

A Dynisco No. C 10V 9049 force transducer was used. It has a
range of 0 to 300 pounds. This was connected to an Autograf model
No. 45 recorder. A 12-volt storage battery provided the excitation
voltage source to the transducer. Due to possible day-to-day variations
in this voltage source, calibration of the transducer and recorder was
made each day of testing.

B. Tables of Results

     Tables I through VI contain the results of the investigation. The designation of sample numbers is as follows: the first letter or letters refer to the type of finish; the second letter indicates tests run on the same surface before regrinding; and the final number indicates the number of runs made on that surface since it was reground. Thus, sample S-B-2 indicates that this is the second test run on a reground, smooth quartz surface. The remaining columns are self-explanatory.

TABLE I. RESULTS OF FRICTION TESTS ON SMOOTH QUARTZ SURFACES

TEST NO.	SAMPLE	TREATMENT	N(kg)	μ	ϕ_μ	REMARKS
600-1	S-A-1	Chemically cleaned	15.03	0.35	19°	1st peak
				0.59	31°	9th peak
600-2	S-A-2	Chemically cleaned	15.03	0.71	35°	1st peak
				0.77	38°	8th peak
600-3	S-B-1	Chemically cleaned	3.67	0.71	35°	1st peak
				0.86	41°	14th peak
600-4	S-B-2	Chemically cleaned	10.48	0.83	40°	1st peak
				0.96	44°	8th peak
600-5	S-B-3	Chemically cleaned	19.56	0.92	43°	1st peak (highest peak)
600-6	S-B-4	Chemically cleaned	28.64	0.85	40°	1st peak
				0.91	42°	5th peak
600-7	S-C-1	Chemically cleaned	28.64	0.56	29°	1st peak
				0.72	36°	3rd peak
				0.87	41°	6th peak
600-8	S-D-1	No cleaning	5.94	0.22	12°	1st peak (highest peak)
600-9	S-D-2	No cleaning, submerged in water	5.94	0.36	20°	1st peak, then sliding w/o slips
				0.45	24°	Leveled off
600-10	S-D-3	Normal cleaning	5.94	0.71	35°	1st peak (highest peak)
600-11	S-D-4	Normal cleaning, submerged in water	5.94	0.73	36°	1st peak
				0.85	40°	2nd peak (highest peak)
600-12	S-E-1	Chemically cleaned, submerged in water	5.94	0.85	40°	1st peak
				0.94	43°	2nd & 3rd peaks
600-13	S-E-2	Chemically cleaned	5.94	0.53	28°	1st peak
				1.06	47°	4-6th peaks
600-14	S-E-3	10 minutes after chemical cleaning	5.94	0.50	27°	1st peak
				0.95	44°	7-9th peaks
600-15	S-E-4	80 minutes after chemical cleaning	5.94	0.41	22°	1st peak
				0.74	37°	9-11th peaks
600-16	S-E-5	150 minutes after chemical cleaning	5.94	0.37	20°	1st peak
				0.55	29°	22nd peak
600-17	S-E-6	255 minutes after chemical cleaning	5.94	0.36	20°	1st peak
				0.44	24°	12-16th peaks
600-18	S-E-7	Chemically cleaned	0.62	1.06	47°	1st peak (highest peak)

TABLE II. RESULTS OF FRICTION TESTS ON ROUGH QUARTZ SURFACES

TEST NO.	SAMPLE	TREATMENT	N(kg)	μ	$\phi\mu$	REMARKS
220-1	R-A-1	Chemically cleaned	15.03	0.22	12°	1st peak
				0.55	29°	3rd-9th peaks
220-2	R-A-2	Chemically cleaned	15.03	0.60	31°	1st peak
220-3	R-A-3	Chemically cleaned including 12% HCl rinse	12.76	0.60	31°	1st peak
220-4	R-A-4	Submerge above in water	12.76	0.55	29°	1st peak
				0.61	31°	7th-8th peaks
220-5	R-B-1	Chemically cleaned including H_2O_2 rinse	15.03	0.56	29°	1st peak
220-6	R-B-2	Chemically cleaned including 10% H_2SO_4	15.03	0.52	27°	1st peak
				0.56	29°	3-7th peaks
220-7	R-A-5	1)Chromic acid,2)distilled water,3)acetone	15.03	0.53	28°	1st peak
220-8	R-B-3	1)Detergent,2)distilled H_2O, 3)acetone	15.03	0.56	29°	1st peak
220-9	R-B-4	Submerge above in water	15.03	0.50	27°	1st peak
220-10	R-B-5	1)Chromic acid,2)distilled water.Submerge in water	15.03	0.54	28°	1st peak
220-11	R-B-6	Let above sit 2hrs,submerged	15.03	0.58	30°	1st peak
220-12	R-B-7	Chemically cleaned	28.64	0.53	30°	1st peak
				0.60	31°	11th peak
220-13	R-B-8	Chemically cleaned	5.94	0.65	33°	1st peak
				0.68	34°	4th peak
220-14	R-C-1	Chemically cleaned	3.67	0.48	26°	1st peak
220-15	R-C-2	Chemically cleaned	3.67	0.52	27°	1st peak
220-16	R-C-3	Chemically cleaned	10.48	0.52	27°	1st peak

TABLE II. CONTINUED

TEST NO.	SAMPLE	TREATMENT	N(kg)	μ	$\phi\mu$	REMARKS
220-17	R-C-4	Chemically cleaned	19.52	0.52	27°	1st peak
220-18	R-C-5	Chemically cleaned	28.64	0.52	27°	1st peak
220-19	R-C-6	Chemically cleaned	37.72	0.52	27°	1st peak
220-20	R-D-1	Iso-propylalcohol vapor rinse	10.48	0.36	20°	1st peak
220-21	R-D-2	Iso-propylalcohol vapor rinse	10.48	0.40	22°	1st peak
220-22	R-D-3	Submerge above in water	10.48	0.43	23°	1st peak
220-23	R-D-4	Chemically cleaned, submerged in water	3.67	0.49	26°	1st peak
220-24	R-D-5		10.48	0.51	27°	1st peak
220-25	R-D-6		19.56	0.51	27°	1st peak
220-26	R-D-7		28.64	0.52	27°	6th peak
220-27	R-D-8		37.72	0.56	29°	3rd peak
220-28	R-E-1	No cleaning	5.94	0.32	18°	1st peak
220-29	R-E-2	No cleaning, submerge in H_2O	5.94	0.41	22°	1st peak
220-30	R-E-3	Normal cleaning	5.94	0.39	21°	1st peak
220-31	R-E-4	Normal cleaning, submerge in water	5.94	0.39	21°	1st peak
				0.42	23°	3rd peak
220-32	R-F-1	Normal cleaning	5.94	0.53	28°	1st peak

TABLE III. RESULTS OF FRICTION TESTS ON VERY ROUGH QUARTZ SURFACES

TEST NO.	SAMPLE	TREATMENT	N(kg)	μ	$\phi\mu$	REMARKS
120-1	VR-A-1	No cleaning	5.94	0.45	24°	1st peak
120-2	VR-A-2	Normal cleaning	5.94	0.50	27°	1st peak
120-3	VR-A-3	Chemically cleaned	5.94	0.50	27°	1st peak
120-4	VR-A-4	Normal cleaning	5.94	0.46	25°	1st peak
120-5	VR-A-5	Submerge 120-4 in water	5.94	0.47	25°	1st peak
120-6	VR-A-6	chemically clean, submerge in water	5.94	0.49	26°	1st peak

TABLE IV. RESULTS OF FRICTION TESTS ON POLISHED QUARTZ SURFACES

TEST NO.	SAMPLE	TREATMENT	N(kg)	μ	$\phi\mu$	REMARKS
P-1	P-A-1	No cleaning	5.94	0.37	20°	no stick-slip
P-2	P-A-2	Normal cleaning	5.94	0.70	35°	1st peak
				0.74	37°	5th peak
P-3	P-A-3	Chemically cleaned	5.94	0.79	38°	1st peak
				1.00	45°	6th peak
P-4	P-A-4	Submerge P-3 in water	5.94	0.84	40°	1st peak
				0.93	43°	2-4th peaks

TABLE V. RESULTS OF FRICTION TESTS ON HAND-GROUND SMOOTH QUARTZ SURFACES

TEST NO.	SAMPLE	TREATMENT	N(kg)	μ	ϕ_μ	REMARKS
H600-1	HS-A-1	No cleaning	5.94	0.40	22°	1st peak
				0.46	25°	13th peak
H600-2	HS-A-2	Normal cleaning	5.94	1.17	49°	1st peak(highest peak)
H600-3	HS-A-3	Chemically cleaned	5.94	0.99	45°	1st peak
				1.08	47°	2nd peak(highest peak)

TABLE VI. RESULTS OF FRICTION TESTS ON HAND-GROUND ROUGH QUARTZ SURFACES

TEST NO.	SAMPLE	TREATMENT	N(kg)	μ	ϕ_μ	REMARKS
H240-1	HR-A-1	No cleaning	5.94	0.84	40°	1st peak
				1.03	46°	2nd peak
H240-2	HR-A-2	Normal cleaning	5.94	0.76	37°	1st peak
				0.85	40°	4th peak
H240-3	HR-A-3	Chemically cleaned	5.94	1.09	47°	1st peak
				1.13	48°	2nd peak
H240-4	HR-A-4	Soaked in 8% HCl for 18 hrs, then chemically cleaned	5.94	0.57	30°	1st peak
				1.07	47°	2nd peak

C. Typical Recorder Traces

Figures 26 and 27 contain typical recorder traces for smooth and rough quartz, respectively. All but two tests were similar to one or the other of these traces. The recorder pen was sweeping from left to right at a constant speed of 0.5 cm/min. The strain dial displacements were marked on the chart periodically and are presented as the horizontal axis. The vertical axis is the vertical movement of the pen. As discussed previously, this deflection is calibrated to give the force on the transducer.

Figure 26 contains a recorder trace for smooth quartz. This type of trace is typical for smooth, polished, and both hand-ground quartz surfaces. This type of plot indicates that as successive stick-slip movements take place, the friction increases. However, it was observed that this increase in friction did not continue indefinitely, but that the friction value leveled off to a constant value. This might be explained by imagining that as the quartz was being sheared, the asperities were "ploughing" away the remaining surface contaminants. Thus, as shearing progressed, more mineral-to-mineral friction was achieved. This increase in friction would stop after the asperities had moved away from their original seats of contact and the contaminants trapped in the original seating. The amount of contaminants still being trapped in the zone of plastic flow during the "ploughing" action would be relatively constant and hence the constant friction value.

The rough and very rough surfaces exhibited characteristics different from the other surfaces, Figure 17. The highest value of friction was typically the first peak. This might be explained in the following manner. The steep asperities of rough and very rough surfaces would

tend to "punch" through the remaining surface contaminating layers much
more easily than the asperities of the apparently smoother surfaces.
This would mean that there would be relatively fewer contaminants
trapped in the zone of plastic flow in the original seating. As shear
progressed and the asperities "ploughed" ahead, there were more surface
contaminants trapped in the new zones of plastic flow than in the
original zone. This increase in contaminants in the contact area
would decrease the friction value.

This explanation would give further weight to arguments already
presented. This indication of the presence of surface contaminants
on the chemically cleaned surface suggests that higher values of friction
may yet be obtained for quartz. The similarity of recorder traces of
hand-ground rough surfaces to those of smooth and polished surfaces
implies that these surfaces contained more rounded or flat asperities
than the rough surfaces produced with the diamond grinding wheel.
This would seem to indicate that the hand-ground surfaces were actually
undergoing a polishing action. This would produce a "fudge" of silicon,
oxygen, and grinding material on the surface. This "fudge" material
does not have the crystalline structure of quartz or even the same
molecular composition. The friction value measured on these surfaces
would actually be a measure of the friction of the amorphous quartz
and metallic compounds that make up the surface. It was for this
reason that the results of hand-ground surfaces were not compared with
those of machine-ground surfaces.

Of the sixty-seven tests only two did not conform to one or the
other of the two types of traces shown. One of these (test. no. P-1)
exhibited no stick-slip whatsoever, giving a smooth curve that leveled

off to a constant value of friction. The other (test no. 600-9)
exhibited one peak before leveling off to a constant value of friction.
Both tests were on dirty surfaces, one polished, the other smooth.
This anomaly was apparently caused by a high degree of surface contam-
ination.

The peak of each stick-slip motion is used in determining the value
of friction. The highest peak value of friction obtained on a test
was considered as the friction value for that test. This value might
be associated with the static value of friction. Other methods for
obtaining a value of friction for each test might be used. One such
method might be to average all the peak values. A method such as this
would mask the existance of the phenomena already discussed in detail
in this section. The difference in peak values is too great to be
ignored or attributed to experimental inaccuracies.

FIGURE 26.   TYPICAL   RECORDER   TRACE   FOR   SMOOTH   QUARTZ

TEST NO. 600-4
N = 10.48 kg.
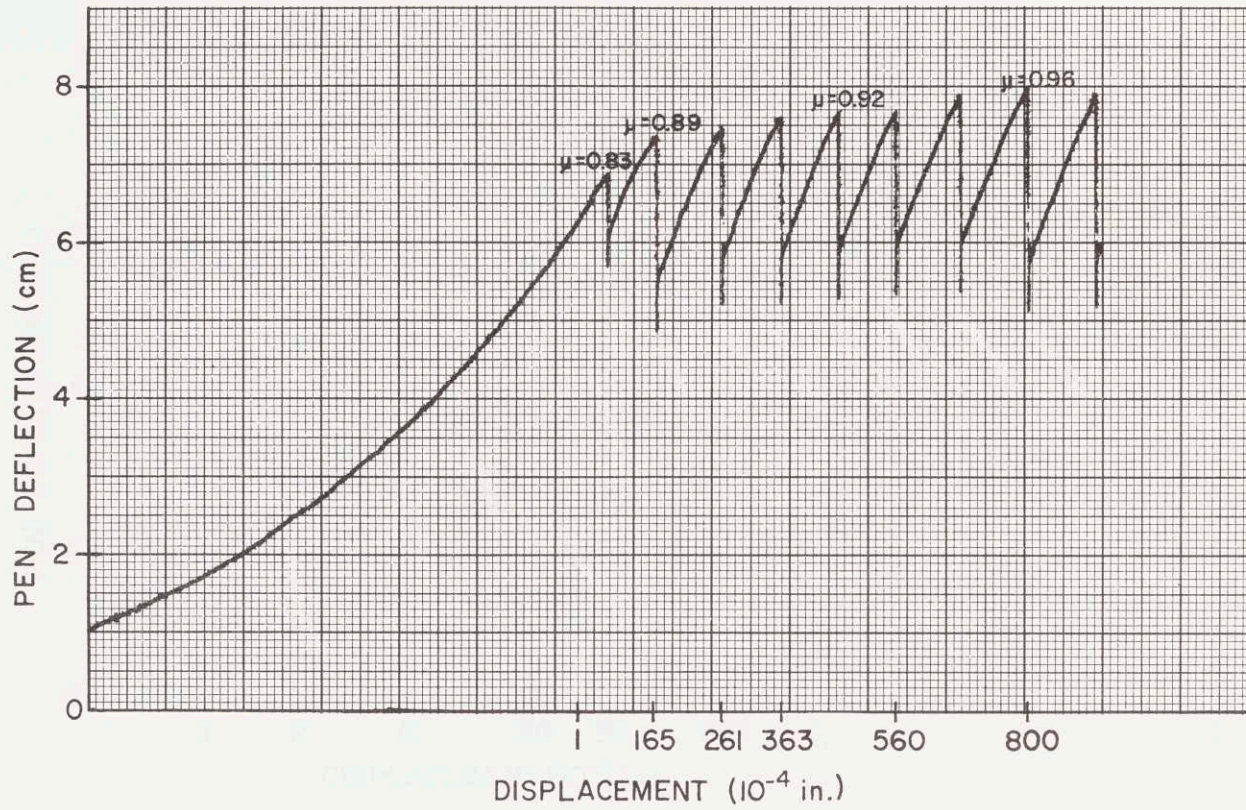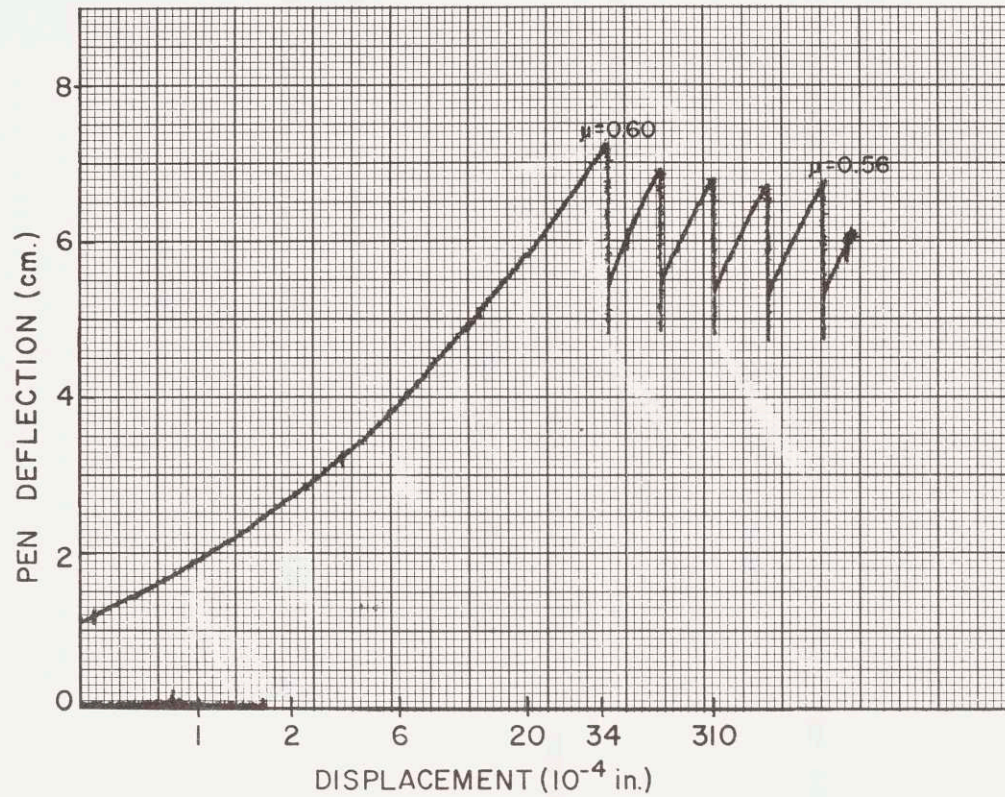Pen Calibration: 1cm = 1.278 kg.

FIGURE 27. TYPICAL RECORDER TRACE FOR ROUGH QUARTZ

TEST NO. 220-2
N = 15.03 kg.
PEN CALIBRATION: 1 cm. = 1.255 kg.

D. Sample Calculations

The following sample calculation is for test no. 600-4, peak no. 8. The recorder trace for this test may also be seen in Figure 26. The following quantities are used in the calculation:

Normal load, N = 10.48 kg

Recorder pen calibration: 1 cm = 1.278 kg

Correction for apparatus resistance, C = 0.1 cm

1. Calculation of true pen deflection due to quartz friction.

True deflection = Recorder chart deflection - correction for

apparatus resistance

= 8.0 cm - 0.1 cm = 7.9 cm

2. Calculation of frictional resistance.

Frictional resistance, T = True deflection x recorder pen calibration

= 7.9 cm x 1.278 kg/cm

= 10.09 kg

3. Calculation of coefficient of friction.

Coefficient of friction, μ = Frictional resistance ÷ normal load

= 10.09 kg ÷ 10.48 kg

= 0.96^{+}

4. Calculation of friction angle.

Tan (friction angle, ϕ_{μ}) = coefficient of friction, μ

= 0.96

ϕ_{μ} = 44°

E. Nomenclature

SYMBOL	DEFINITION	UNITS
A_c	Actual area of contact	cm^2
C.L.A.	Center-line-average	in
d	Diameter	cm
N	Normal force	kg
q_u	Normal stress to cause yielding	kg/cm^2
R_1	Radius of curvature	cm
R_2	Radius of curvature	cm
s	Shear strength	kg/cm^2
T	Frictional resistance or shear force	kg
δ	Geometric and material property	cm^2/kg
μ	Coefficient of friction	dimensionless
ν	Poisson's ratio	dimensionless
ϕ_m	Peak friction angle of a mass of soil	degrees
ϕ_μ	Mineral-to-mineral friction angle	degrees

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