CHAPTER VI

EXPERIMENTAL INVESTIGATIONS

6.1 GENERAL

The behaviour of sliding along joint has been the subject of experimental investigations for many research workers. Various concepts as regards shearing behaviour of rock is a result of number of investigations, carried out utilising various testing techniques. It is seen through literature survey that different systems of measuring frictional properties along joint have been employed. The most notable among these are :

(i) Slider sliding over another surface

(ii) Single and double shear tests

(iii) Direct shear test

(iv) Triaxial shear test

(v) In situ shear test

The principles underlying these methods can be schematically represented as shown in Fig. 6.1. Recognizing the influence of testing technique on the findings of investigations, different research workers attempted to develop and employ different testing techniques.

6.2 REVIEW OF EXPERIMENTAL SET UPS

6.2.1 Slider sliding over another surface

During earlier investigations on sliding characteristics

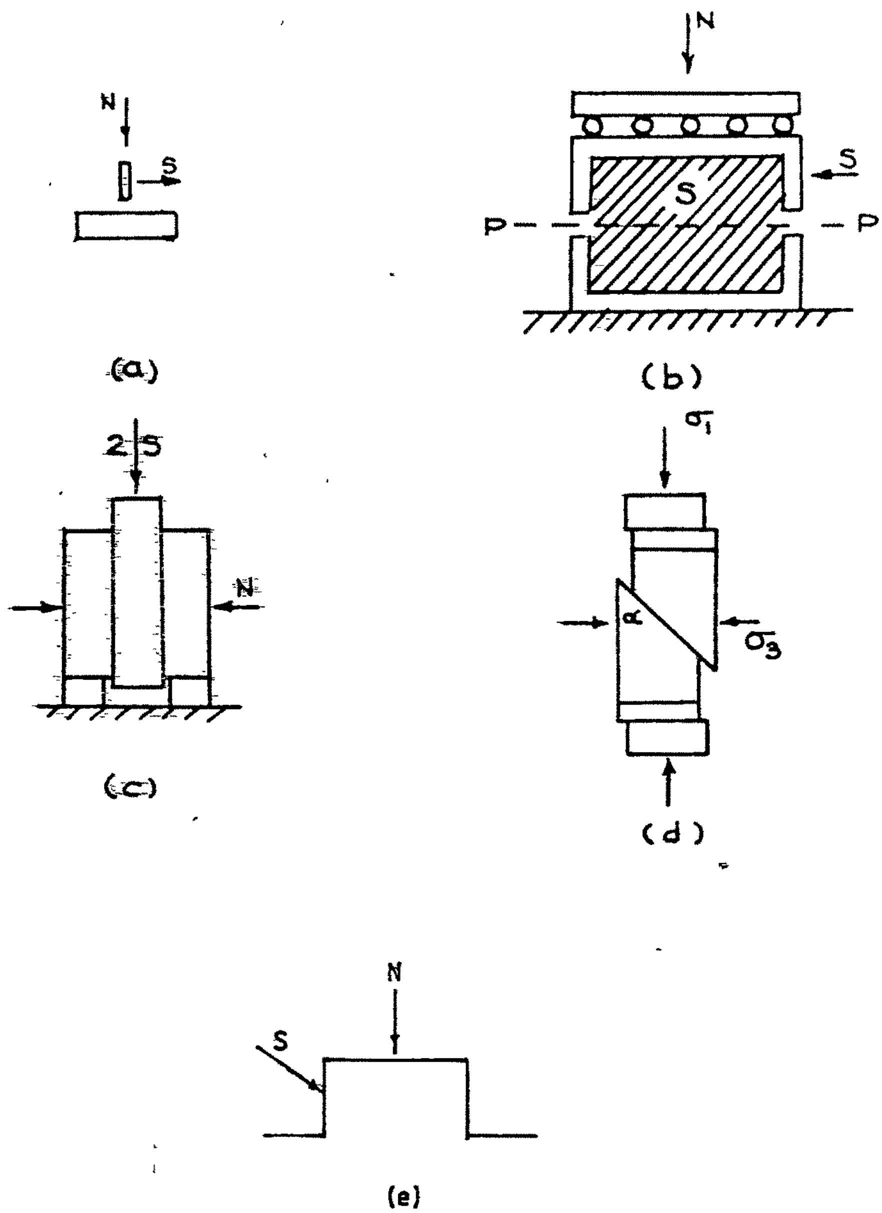


FIG: 6·1 SYSTEMS OF MEASURING FRICTION PROPERTIES ALONG JOINTS

(a) SLIDER SLIDING ON ANOTHER SURFACE
(b) CONVENTIONAL SHEAR BOX TEST ARRANGEMENT
(c) DOUBLE SHEAR TEST ARRANGEMENT
(d) TRIAXIAL TEST ARRANGEMENT
(e) IN SITU SHEAR TEST

of minerals and rocks, Horn and Deere (1962), Byerlee (1967) and Jeager and Cook (1969) adopted a testing set up normally employed in the study of metal friction. According to Bowden and Tabor (1950), a small slider, hemispherical in shape, is made to slide on a large surface in which case normal load is limited (Fig. 6.1-a). The method is more suitable to study wear rather than friction and does not represent actual condition occuring in nature. Renger (1971) modified the technique by using two sliding blocks of different sizes and with provision of large surfaces. The important problem posed by such an arrangement was that it was difficult to ensure uniformity of normal load over the whole of the surface at different stages of movement of blocks. Ranger solved this difficulty by building a special loading machine where the normal force was applied by air pressure rubber bellows (Fig. 6.2). The shear force was applied through two cylinders and was measured by a load cell. More recently, a number of servo-controlled shear machines have been designed and put into operation using this method. This method has certain advantages over other methods. It permits ease of determination of dilation and a relatively greater amount of movement between the surfaces. The sliding surfaces are available for visual observation at any stage of the test.

6.2.2 Single and double shear tests

In this test a square prismatic specimen is rigidly held in a special fixture with one end protruding. Through a slot in the fixture a shearing cutter with a straight cutting edge can be moved. The disadvantages of this set up is the occurrence of bending stresses which can not be measured, and the stress concentration caused by the cutting edge. The method was used by Protodyakonov (1969).

A modification of the single shear test is the double shear test where the shear load is applied through a testing

A B - 50 MPa HYDRAULIC CYLINDERS
C D E LOAD CELLS
F AIR BELLOWS
I UPPER BLOCK
II LOWER BLOCK
1 2 3 4 5 LVDT FOR VERTICAL AND HORIZONTAL DISPLACEMENT

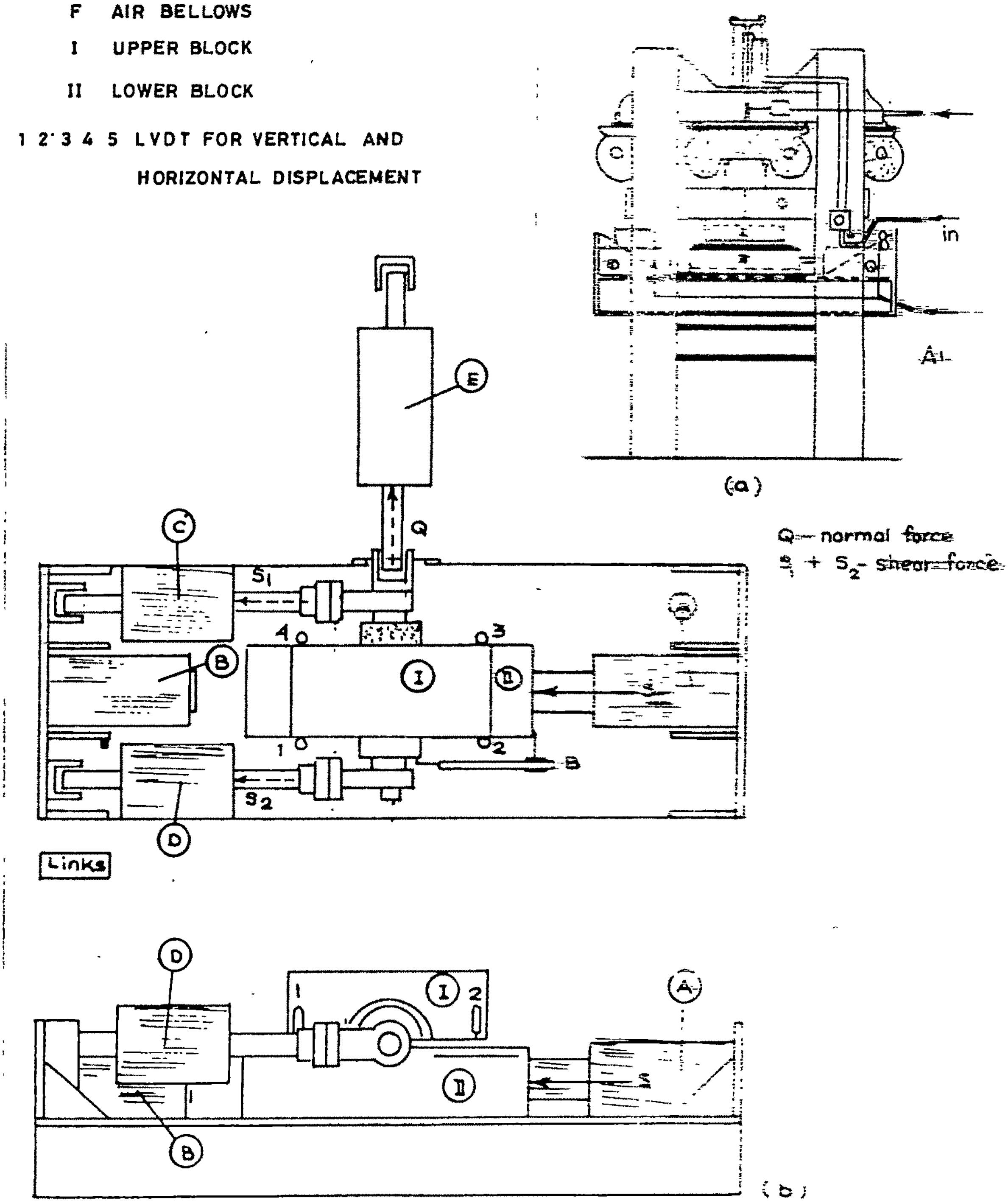


FIG: 6·2 LARGE FRICTION MACHINE

(A) OVERALL VIEW OF MACHINE

(b) LOCATION OF CYLINDERS, LOAD CELLS & LVDTS

(after RENGERS 1971)

machine or a jack. The principle of the test is shown in Fig. 6.1-c. The method was used by a number of investigators such as Hoskins, Jeager and Rosengren (1968), Rosengren (1968), Jeager and Rosengren (1969) and Dieterich (1972). The method is particularly suitable for the determination of friction along the contact surfaces of a rock or frictional force along a surface which has been artificially prepared. The method is, however, not suitable when shear along a discontinuous joint is to be studied.

6.2.3 Direct shear test

(i) Conventional box shear test

Conventional shear box is used by a number of investigators such as Yevdokimov and Serpegin (1967), Krasmanovic (1967), Hoek and Pentz (1969), Lama (1974). The method consists of setting the rock specimens, cylindrical, prismatic or of irregular shape, with the joint plane at the mid half of the shear box. Rock specimen is cast in mortar or plaster of paris with joint plane accurately located at the predetermined position in the mould. In a method used by Locher (1968) as shown in Fig. 6.3, two hydraulic jacks exert the normal force (N) and the shear force (S). Since the transmission of the normal force is through proving rings, the system suffers from the disadvantage that any dilation or contraction changes the value of the normal force. The arrangement used by Krasmanovic (1967) is shown in Fig. 6.4. The normal force is applied through two hydraulic cylinders and the shear force by four cylinders. The setting of the apparatus is such that the applied shear force makes an angle of 4° with the shear surface so that the shear strength can be determined with minimum of disturbance even at small normal loads. As vertical load is applied through hydraulic cylinders the measurement of dilation is not possible. The change in pressure in the cylinders applying vertical load may be

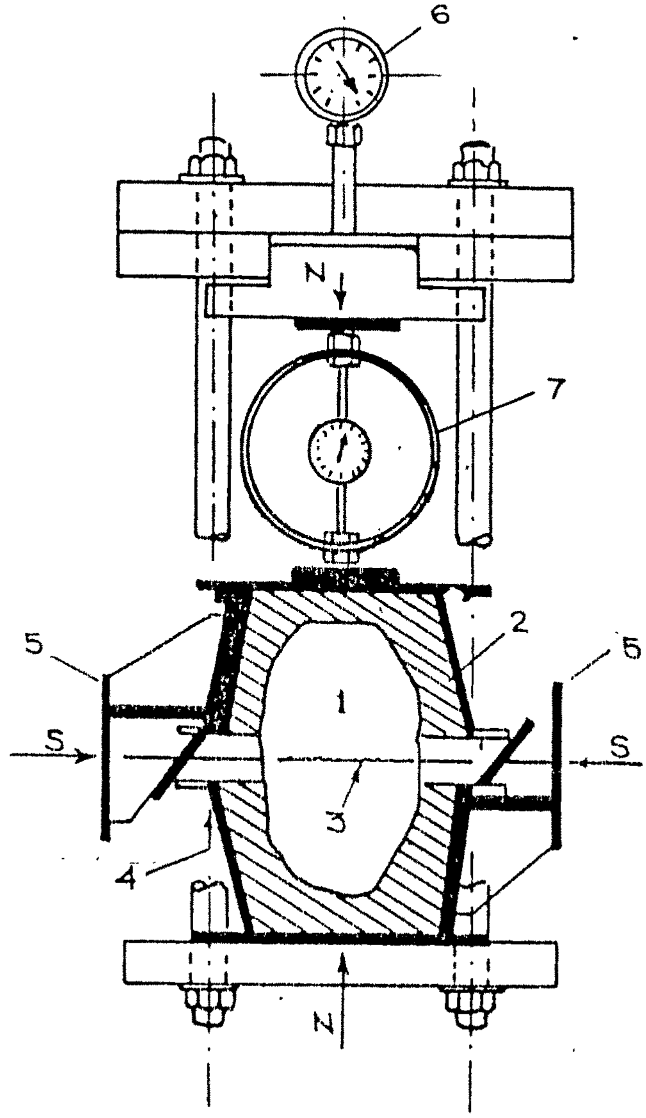


FIG: 6·3 SCHEMATIC LAYOUT OF SHEAR TESTING APPARATUS

1. Sample 2 Mortar 3 Discontinuity
4 Double steel form 5 Exchangable shoes transmitting force S 6 Manometer for high loads & control of force N 7 Proving ring for force N (Proving ring for force S not shown)

(after LOCHER, 1968)

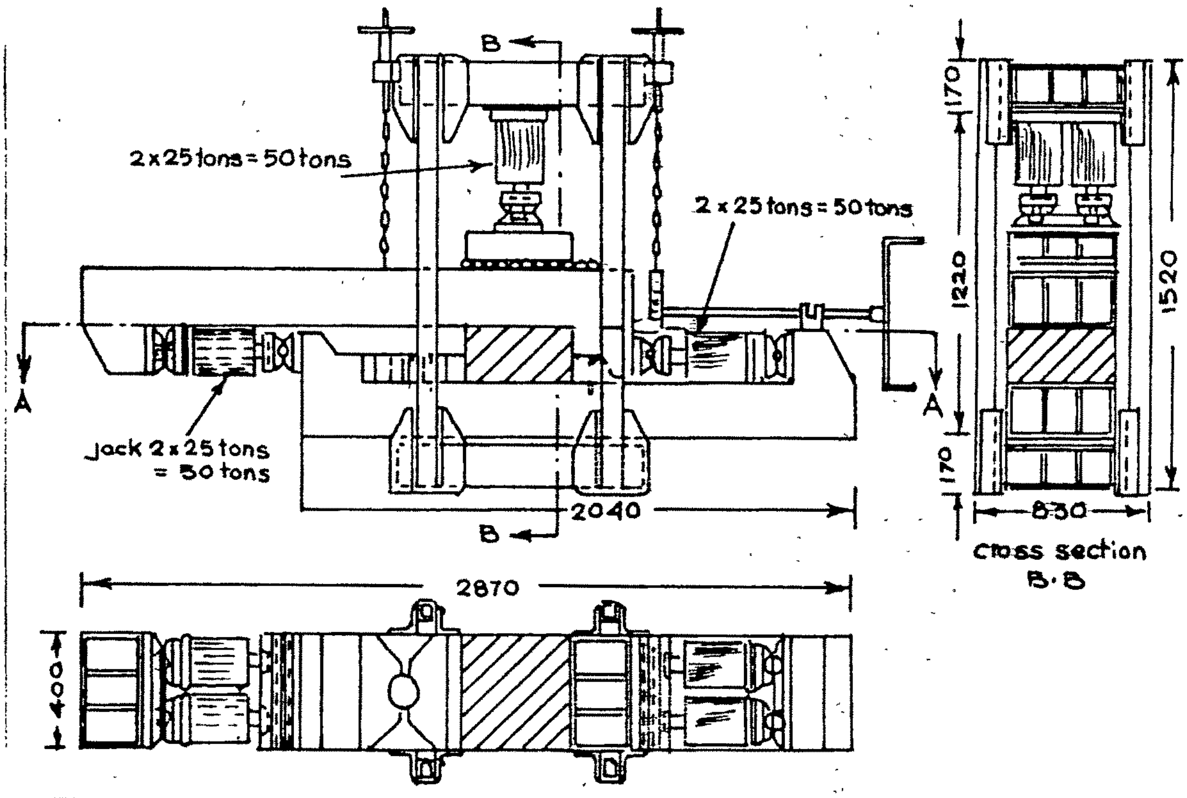


FIG: 6·4 SCHEMATIC DIAGRAM OF THE 0·5 / 1·0 MN (50/100 tons) SHEARING APPARATUS

(after KRSMANOVIC 1967)

monitored using transducers. The system has also the disadvantage that vertical constraint of the specimen is uncertain unless it is monitored.

Patton (1966) used a direct shear machine with the modification that normal force remains stationary and the bearing friction was greatly eliminated by making the lower block move on the roller bearings, the upper block remaining in a stationary position (Fig. 6.5). The shear force is measured by two load cells attached to the tension tie bar. The vertical and the horizontal displacements are measured by using LVDT-S. The method has an advantage that the dilation can be measured for any value of normal load. A similar arrangement was also used by Coulson (1970).

In the direct shear set up used in the present investigation the normal load is applied through a lever system by dead weights and is held constant during the test. The shear load is applied through motorised system and is measured by relatively stiff proving ring system. The deformations in normal and shear directions are measured through dial gauges having an accuracy of 0.01 mm. Capacity of normal loading system is 300 kg and that of proving ring of shear loading 250 kg. Different rates of strains that are possible to be adjusted for shear loading are 1.25, 0.3125, 0.25, 0.0625, 0.05, 0.0125, 0.01, 0.0025, 0.002 and 0.005 mm/min.

(ii) Cyclic direct shear test

The cyclic direct shear test apparatus is designed for a maximum normal load of 5000 kg and a maximum shear load of 15000 kg. It accomodates boxes of 10 cm x 10 cm x 10 cm size and 15 cm x 15 cm x 15 cm size, It gives 72 different rates of strains. Normal load application is through a yoke and lever system. A special locking arrangement is made for cyclic application of shear load. Shear load is applied in

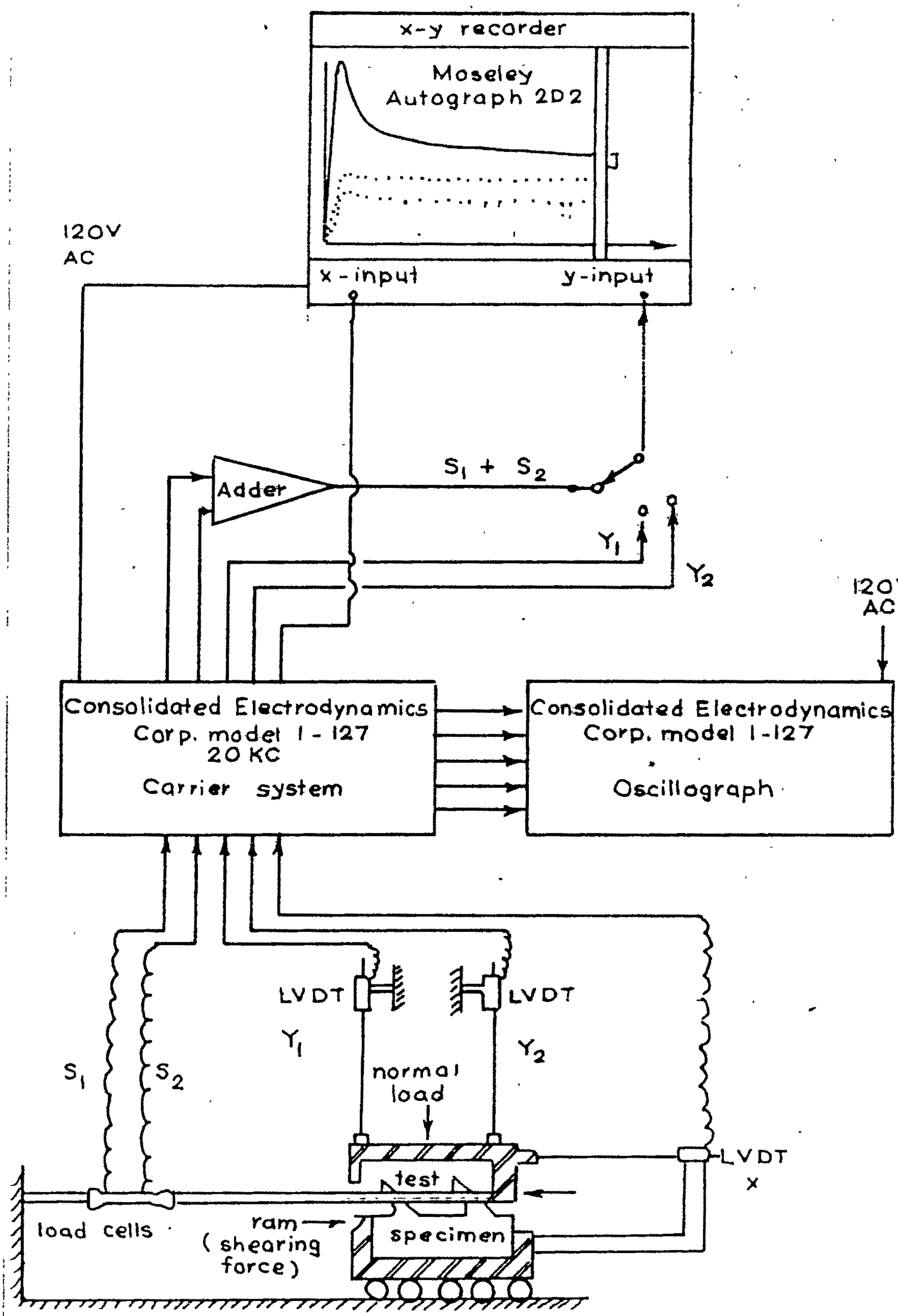


FIG. 6·5 SCHEMATIC DIAGRAM OF THE TESTING AND RECORDING EQUIPMENT.
(after PATTON, 1966).

cyclic manner using a forward reverse switch fitted on the frame. Shah (1987) employed this set up for investigations.

(iii) Dynamic Direct shear apparatus

Gould has described a dynamic direct shear apparatus. The apparatus is designed to receive a rock sample with joint surface dimensions of 20.3 x 20.3 cm. The overall sample height is 10.2 cm. Normal stress ranging from zero to 17.77 MPa can be applied with servo-controlled hydraulic actuator. Shear displacement frequencies can be varied from 0 to 10 Hertz. The assembled apparatus is shown in Fig. 6.6. Shear stress can be applied from zero to 3.77 MPa. The shear box has four degrees of freedom which are pitch and roll motion and vertical and horizontal translation. The normal and shear forces are generated by MTS servo controlled hydraulic actuators, operating independently in separate closed loop control system. A schematic of the MTS operating and control system is shown in Fig. 6.7. A Hewlett packard 3054 A Automatic Data Acquisition/Control System, controlled by a HP 9825 B disk counter, is used.

(iv) Hutson and Dowding (1985) have described the interfacing of a general purpose micro computer to a MTS system and its subsequent use in shearing rock joints under conditions of controlled normal deformation.

6.2.4 Triaxial Test

(i) Conventional Triaxial Test

Triaxial apparatus is most extensively used. Jeager (1969) used it for the study of variety of artificially prepared joints in rock. The method consits in using a cylindrical specimen with a joint plane suitably oriented at an angle to the axis of the specimen. The specimen

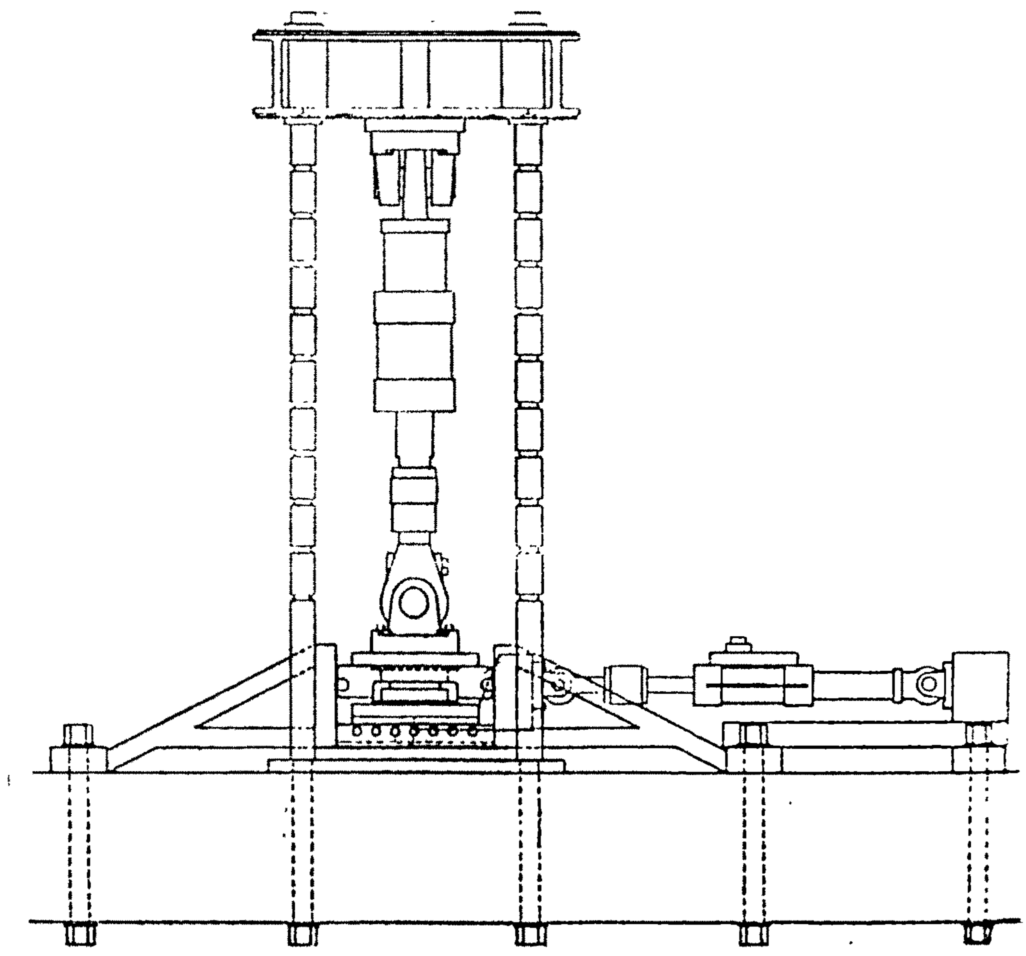


FIG: 6·6 DYNAMIC DIRECT SHEAR APPARATUS (Gould)

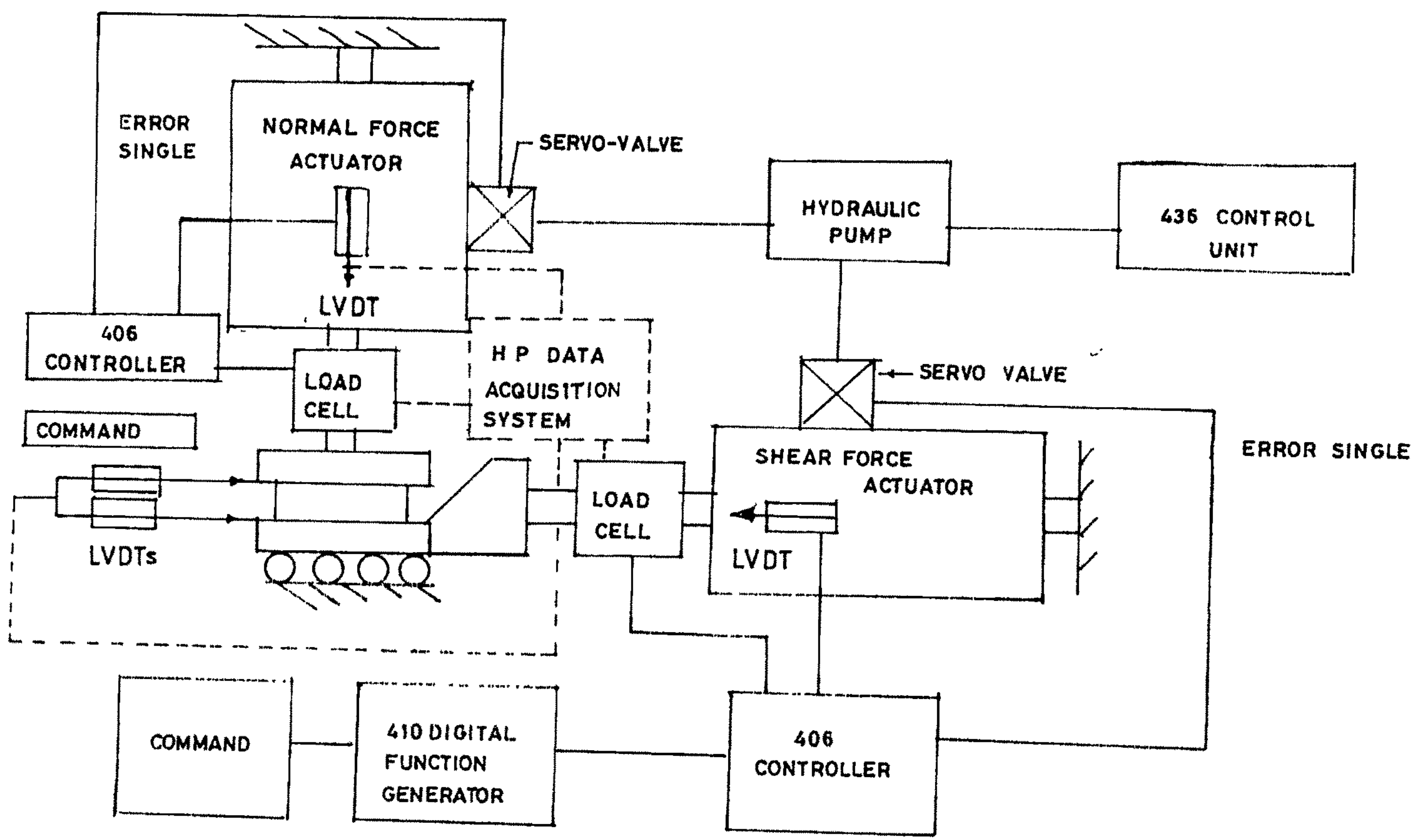


FIG: 6·7 SCHEMATIC OF MTS SYSTEM (Gould) is subjected to a lateral and axial pressure in a triaxial cell. Because of the simplicity number of investigators viz : Lane and Heck (1964), Murrel (1965), Hobbs (1966, 1970), Byerlee and Brace (1968) preferred a triaxial test set up to study the behaviour of jointed rocks. However the method suffers from certain drawbacks. It does not permit independent variation of shear force and the normal force. The method is not suitable for study under low normal stresses. There are certain other difficulties due to the geometry of the testing apparatus. As displacement proceeds the stress system changes so that the resusts are accurate only for the initiation of sliding. In the case of no spherical seat there are certain lateral stresses introduced depending upon the lateral stiffness of the machine. In case of one spherical seat there is rotation of the part of the specimen in contact with the spherical seat while the other part does not change its position. With two spherical seats the area of contact changes and frictional and lateral forces are introduced at the seats.

(ii) True Triaxial Test

Several multiaxial devices have been designed and constructed. In these devices the triaxial loading system have been designed such that it provides independent control of the applied pressure in each of the three principal loading directions. A truly triaxial or multiaxial device referred to by Desai et al (1982) is shown in Fig. 6.8, which permits application of three independent (principal) stresses, σ_1, σ_2, σ_3, on six faces of a cubical specimen. Any path of loading in the three dimensional stress space can be followed. Main components of the loading system developed by michelis (1985) are diagramatically shown in Fig. 6.9 (a to d). The cell consists of a cylinder in which the body is acting as reaction frame for application of intermediate and minor pressures. The cell is symmetrical about longitudinal axis of the prismatic specimen. Two pressure vessels filled with hydraulic oil and pressurised by

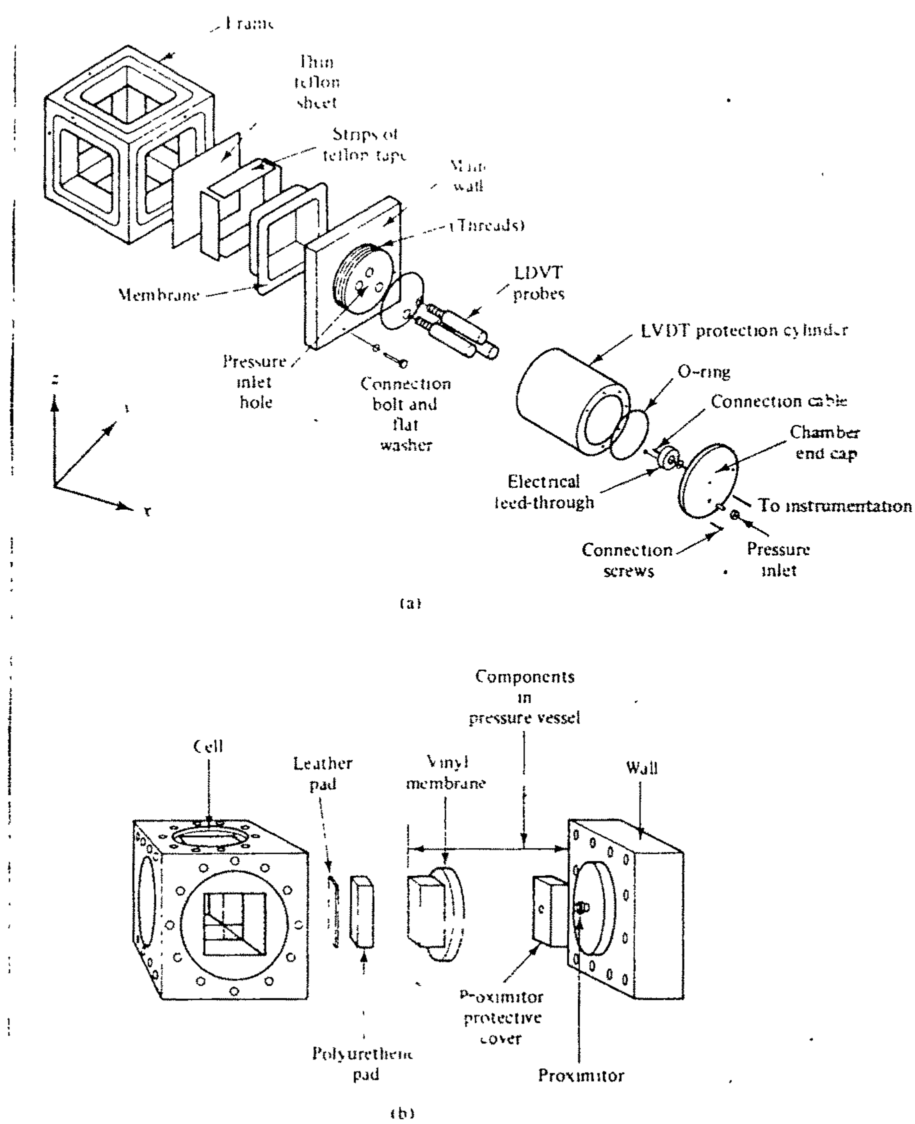


FIG: 6·8 TRULY TRIAXIAL OR MULTIAXIAL DEVICES

(a) CAPACITY 200 psi (1·38 MPa) (b) CAPACITY 20000 psi (138 MPa)

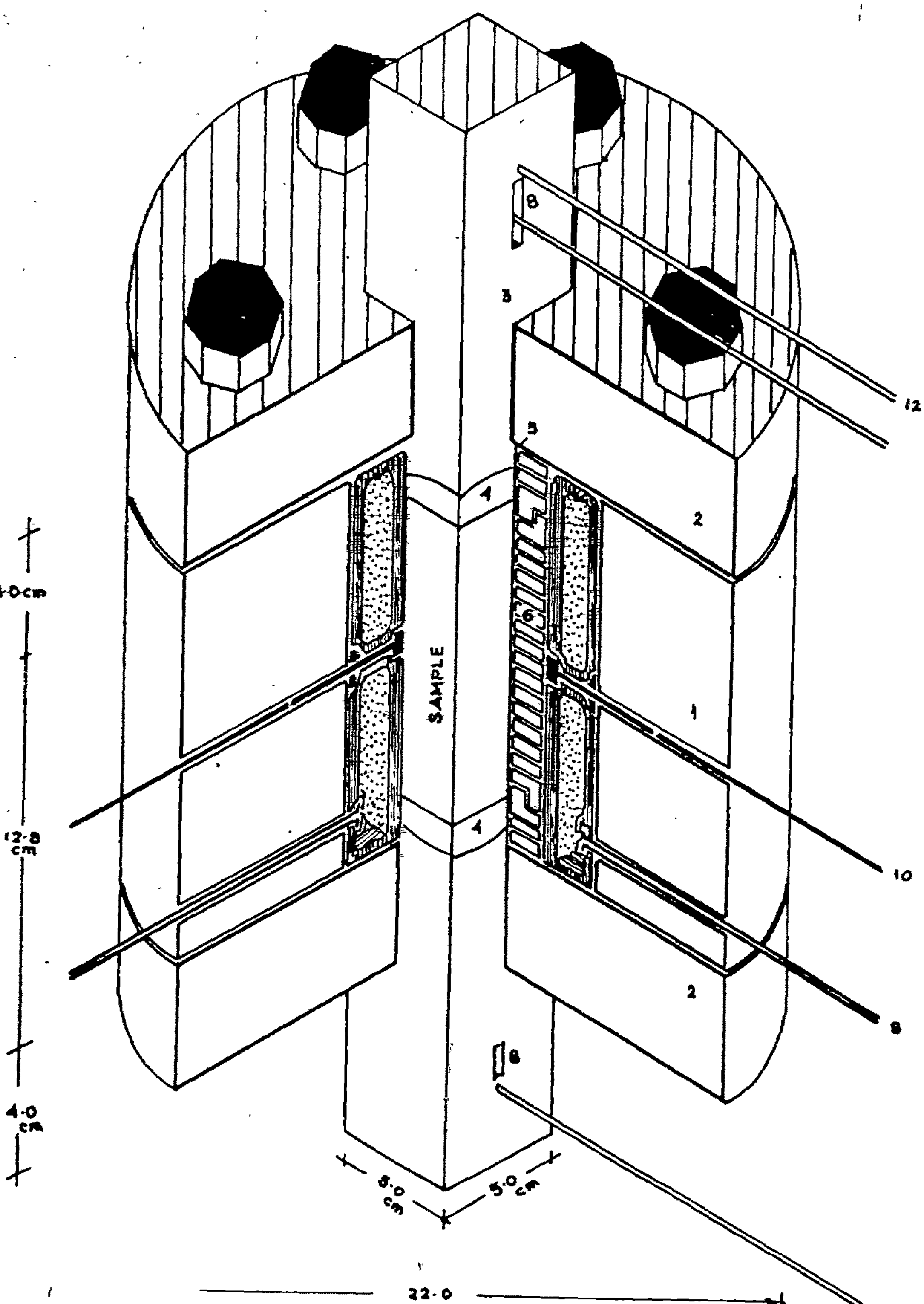


FIG: 6·9(a) CUTAWAY VIEW OF THE POLYAXIAL CELL.

1. Cylindrical body; 2. Cylindrical plates; 3. Piston; 4: Spherical seats; 5. Two very thin copper sheets; 6: Steel prisms; 7. PVC bag; 8. (upper): Partial axial strain measuring rod; 8. (lower) exit for pore water & strain gauge cables; 9. High pressure tube for filling & pressurizing the PVC bags with oil; 10, Lateral strain measuring rod; 11, 12: Total axial strain measuring rods.

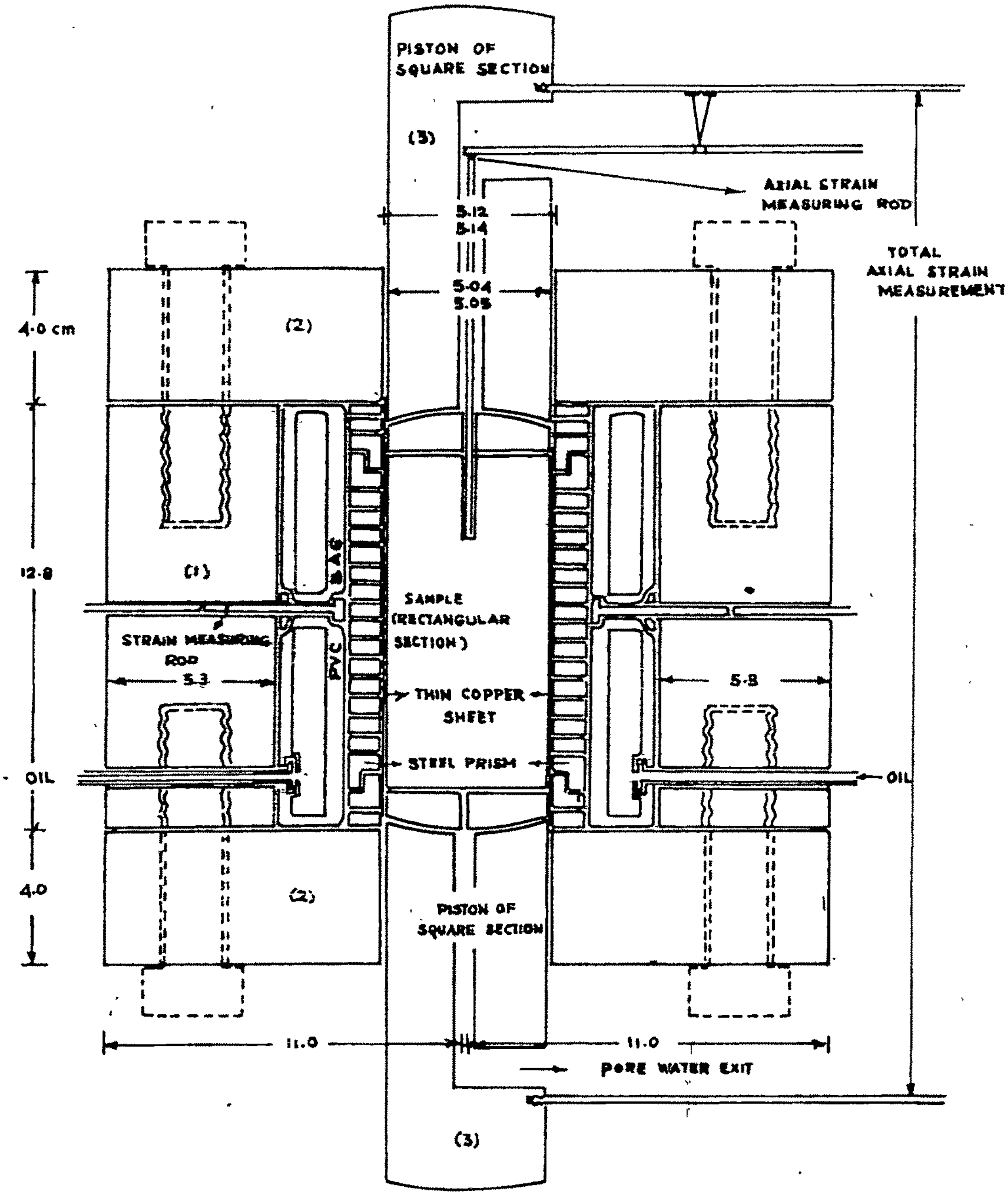


FIG: 6.9 (b) DESIGN OF POLYAXIAL CELL : Longitudinal section.

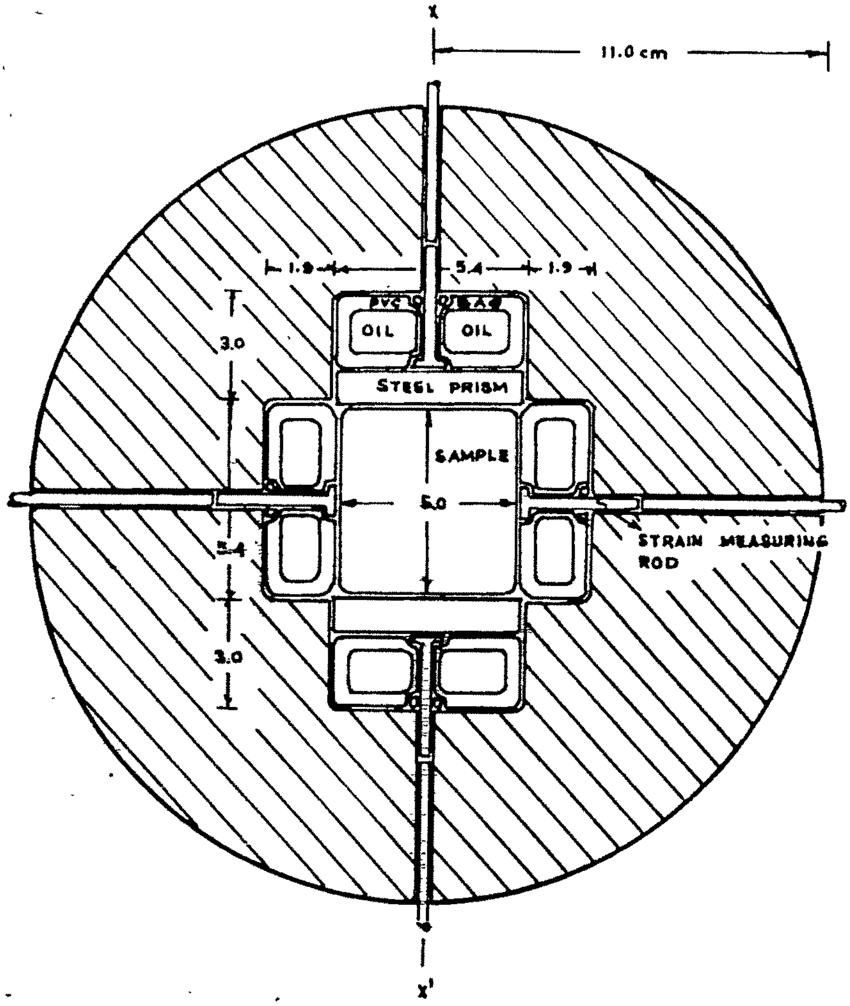


FIG 6.9(c) DESIGN OF POLYAXIAL CELL: Cross-section

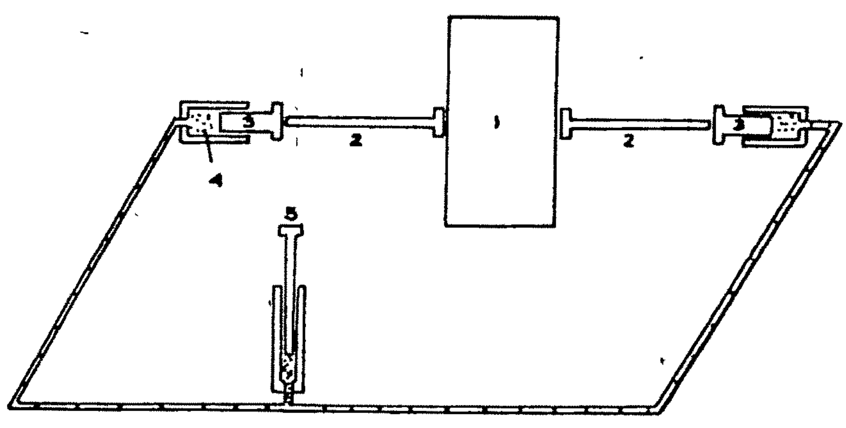


FIG: 6.9 (d) SCHEMATIC PRESENTATION OF LATERAL DEFORMATION ($\varepsilon_2, \varepsilon_3$) MEASURING DEVICE.

two servo controlled testing machines are normally required to generate and control the minor and major principal stresses. The intermediate pressure is applied by two steel prisms. The test set up facilitates to conduct test under varieties of stress paths. These are basically stress controlled test set ups. There could be drawbacks arising out of mix loading conditions at the specimen edges.

6.2.5 In situ shear test

In situ shear test is conducted on weak discontinuties present in the rock mass which cannot be sampled for laboratory testing. The test essentially consists of carving out a block of rock resting on the undisturbed discontinuity. The block is surrounded by concrete to have even surfaces. The normal and shear loads are applied through hydraulic jacks. In order to avoid tensile stresses generated due to bending, the shear jack is placed at an angle with horizontal such that the line of action of normal load and shear load coincide at the centroid of the contact area. A typical test set up is shown in Fig.6.10. Datir (1981) utilized this set up for in situ testing.

6.2.6 Data acquisition system (DAS 4000)

Recently data acquisition system is available for use alongwith transducers for acquisition of data during a direct shear or triaxial test. The MICRODATE 4000 is a microprocessor controlled data acquisition system. The system is configurated as 8 or 16 channel master unit and can be extended up to 256 channels. It is designed to accept any type of strain gauge based transducer or strain gauge bridges. The output of data logger can be obtained on any standard 80 column Dot Matrix Printer. It is equipped with a built in calender clock to display time in hour-minute-second and date in date-month-year. The time and date can be set up during initial set up.

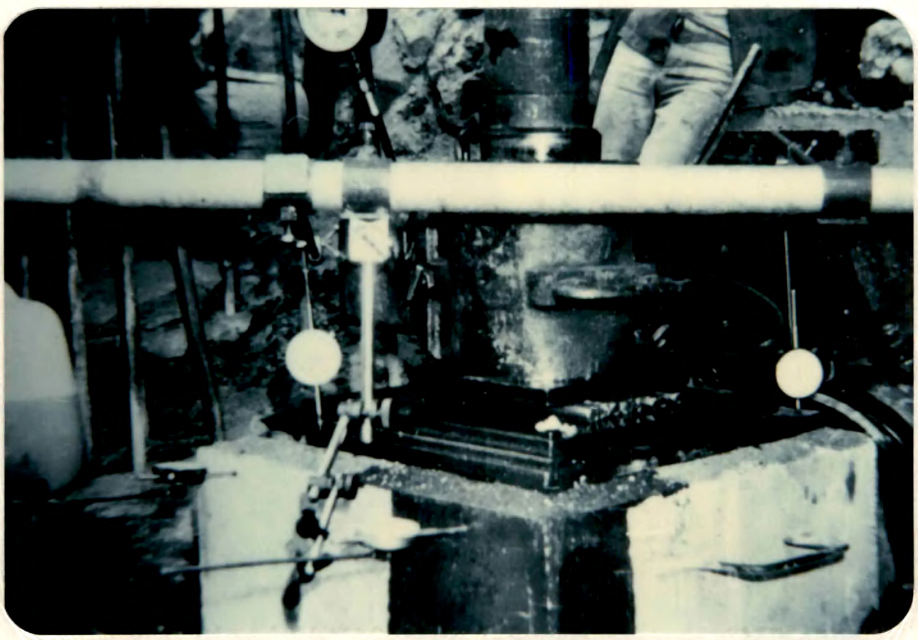


FIG: 6·10 A TYPICAL SET UP OF INSITU SHEAR TEST

MICRODATA 4000 is provided with RS 232 C interface which enables computer link up for loading of acquired data on a floppy. It is supplied with a floppy diskette containing package which helps user in establishing a computer link between data logger and computer. Fig 6.11 show such a system.

6.2.7 The M.T.S. System (MTS 810)

This is a servo-controlled electro-hydraulic system with automatic control of different (static/dynamic) loading combinations, display and printer facility up to 6 channels. The system consists mainly of 3 units :

(i) Load unit

(ii) Performance Package

(iii) Control Package

The details of each unit are as under :

(i) Load Unit :

It consists of following :

(a) **Actuator :** To apply load to test specimen as per programme.

(b) **Loading Frame :** with adjustable crosshead.

(c) **Stiff Load Cell :** for monitoring load on specimen.

(ii) Performance Package

This consists of a hydraulic power supply unit connected to other units through servo valves which controlls the hydraulic power rate. Servo valves are normally mounted on ACTUATOR via MANIFOLD. MANIFOLD provides hydraulic filteration and supresses line pressure fluctuations in high

FIG: 6·11 DATA PROCESSOR WITH COMPUTER

response hydraulic actuators.

(iii) Control Package

This consists of main CONTROL cabinet with different control units accomodated in it. Main control units are, controller, function generator, control panel, counter panel, modular testing panel, data display, recorder and phase shifter. Fig. 6.12 indicate the control panel of the MTS system. Gandhi (1987) employed this MTS system for investigations.

6.2.8 To establish the canon of basic concept it is desirable to work on an experimental set up which has the least probability of distortion of observations and for this a simplest set up is the best set up. While for delineating the actual behaviour the essential requirement is the verification of the field observations against the rationally developed mathematical equations based on established concent.

6.3 CONCEPT VERIFICATION AGAINST EXPERIMENTS

6.3.1 The first requirement is the establishment of the basic concepts of sliding along surfaces. Resistance to sliding is known as friction. Friction along a joint is dependent upon the characteristics of the joint surfaces and the properties and thickness of the filling material. During sliding along a joint, volume change occurs. Following experiments should contribute towards the clear exposition of the phenomenon of sliding.

(i) Direct shear box tests on unlubricated plane surfaces without any apparent asperities.

(ii) Direct shear box tests on lubricated plane surfaces without any apparent asperities.

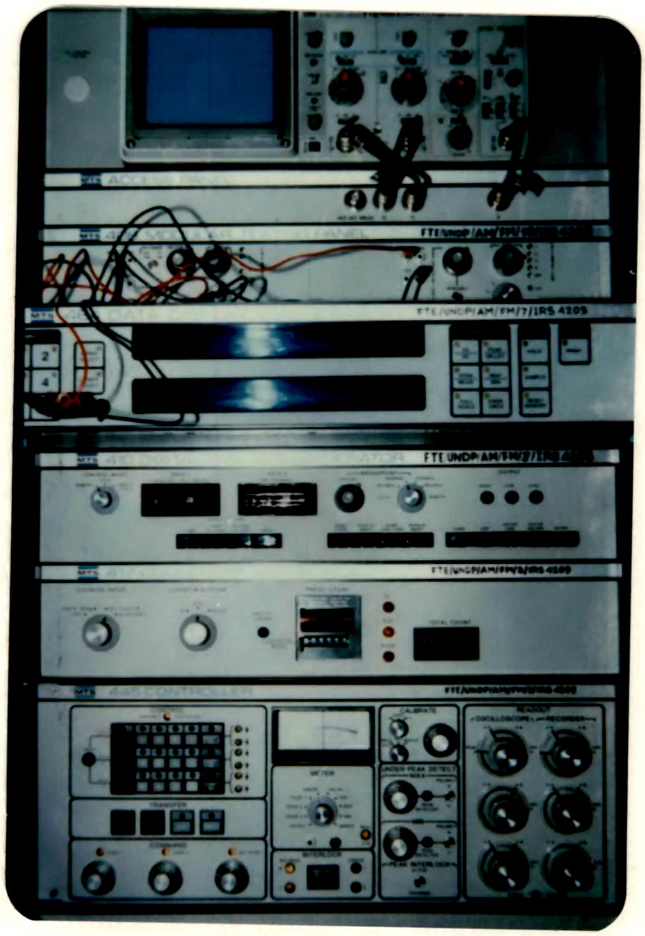


FIG: 6·12 MTS CONTROL PANEL

(iii) Direct shear box tests on surfaces having regular asperities.

(iv) Direct shear box tests on plane surfaces with irregular asperities.

(v) Direct shear box tests on gouged plane surfaces.

6.3.2 Observations of tests conducted on unlubricated plane surfaces without any apparent asperities are presented in Table 6.1 to 6.3. Plots of shear stress (σxy) versus shear displacement (du) and those of normal displacement (dv) with shear displacement (du) are shown in Fig. 6.13. Coulomb plot for this set of tests is drawn in Fig. 6.14.

6.3.3 Observations of tests conducted on lubricated plane surfaces without any apparent asperities are presented in Table 6.4 to 6.6. Plots of shear stress (σxy) versus shear displacement (du) and that between normal displacement (dv) and shear displacement (du) are shown in Fig. 6.15. Coulomb plot is presented in Fig. 6.16.

6.3.4 Observations of tests conducted on surfaces with regular asperities are presented in Table 6.7 to 6.9. Variation of shear stress (σxy) with shear displacement (du) is plotted in Fig. 6.17. Relation between vertical displacement (dv) and horizontal displacement (du) is shown in Fig. 6.18. Coulomb plot is shown in Fig. 6.19.

6.3.5 Observations of tests conducted on plane surfaces having irregular asperities are presented in Table 6.10 to 6.12. Variation of shear stress (σxy) versus shear displacement (du) and that of vertical displacement (dv) with shear displacement (du) are shown in Fig. 6.20. Coulomb plot is shown in Fig. 6.21.

TABLE 6.1 : SAMPLE OF UNLUBRICATED PLANE SURFACE

Sample T_1B_1 Normal Stress = σyy = 1.0 kg/cm^2 (constant)

Sr. No.	Shear stress 'σxy' in Kg/cm^2	Normal displacement 'dv' in cm	Shear displacement 'du' in cm
1	2	3	4
1	0.15	0.005	0.064
2	0.29	0.006	0.078
3	0.59	0.006	0.103
4	0.74	0.005	0.115
5	0.88	0.003	0.133
6	0.95	0.002	0.146
7	0.95	0.001	0.165
8	0.91	0.001	0.234
9	0.88	0.000	0.305
10	0.85	-0.002	0.320
11	0.79	-0.002	0.327

TABLE 6.2 : SAMPLE OF UNLUBRICATED PLANE SURFACE

Sample T_2B_2 Normal Stress = σ_{yy} = 1.5 kg/cm^2 (constant)

Sr. No.	Shear stress 'σ_{xy}' in kg/cm^2	Normal displacement 'dv' in cm	Shear displacement 'du' in cm
1	2	3	4
1	0.15	0.007	0.053
2	0.29	0.008	0.067
3	0.44	0.009	0.088
4	0.59	0.011	0.102
5	0.74	0.011	0.116
6	0.88	0.011	0.133
7.	1.03	0.009	0.153
8.	1.18	0.007	0.174
9.	1.33	0.005	0.206
10	1.39	0.003	0.276
11	1.43	0.002	0.438
12	1.41	0.000	0.476
13	1.38	-0.001	0.518
14	1.35	-0.001	0.538

TABLE 6.3 : SAMPLE OF UNLUBRICATED PLANE SURFACE

Sample T_3B_3 Normal Stress = σ_{yy} = 2.0 kg/cm^2 (constant)

Sr. No.	Shear stress 'σ_{xy}' in kg/cm^2	Normal displacement 'dv' in cm	Shear displacement 'du' in cm
1	2	3	4
1	0.15	0.002	0.006
2	0.29	0.003	0.014
3	0.44	0.007	0.025
4	0.74	0.009	0.044
5	1.03	0.009	0.064
6	1.18	0.007	0.076
7	1.47	0.005	0.102
8	1.62	0.003	0.114
9	1.77	0.002	0.126
10	1.92	0.001	0.139
11	1.98	0.000	0.148
12	1.95	-0.001	0.176
13	1.92	-0.003	0.211
14	1.89	-0.004	0.223
15	1.84	-0.006	0.253
16	1.81	-0.008	0.322

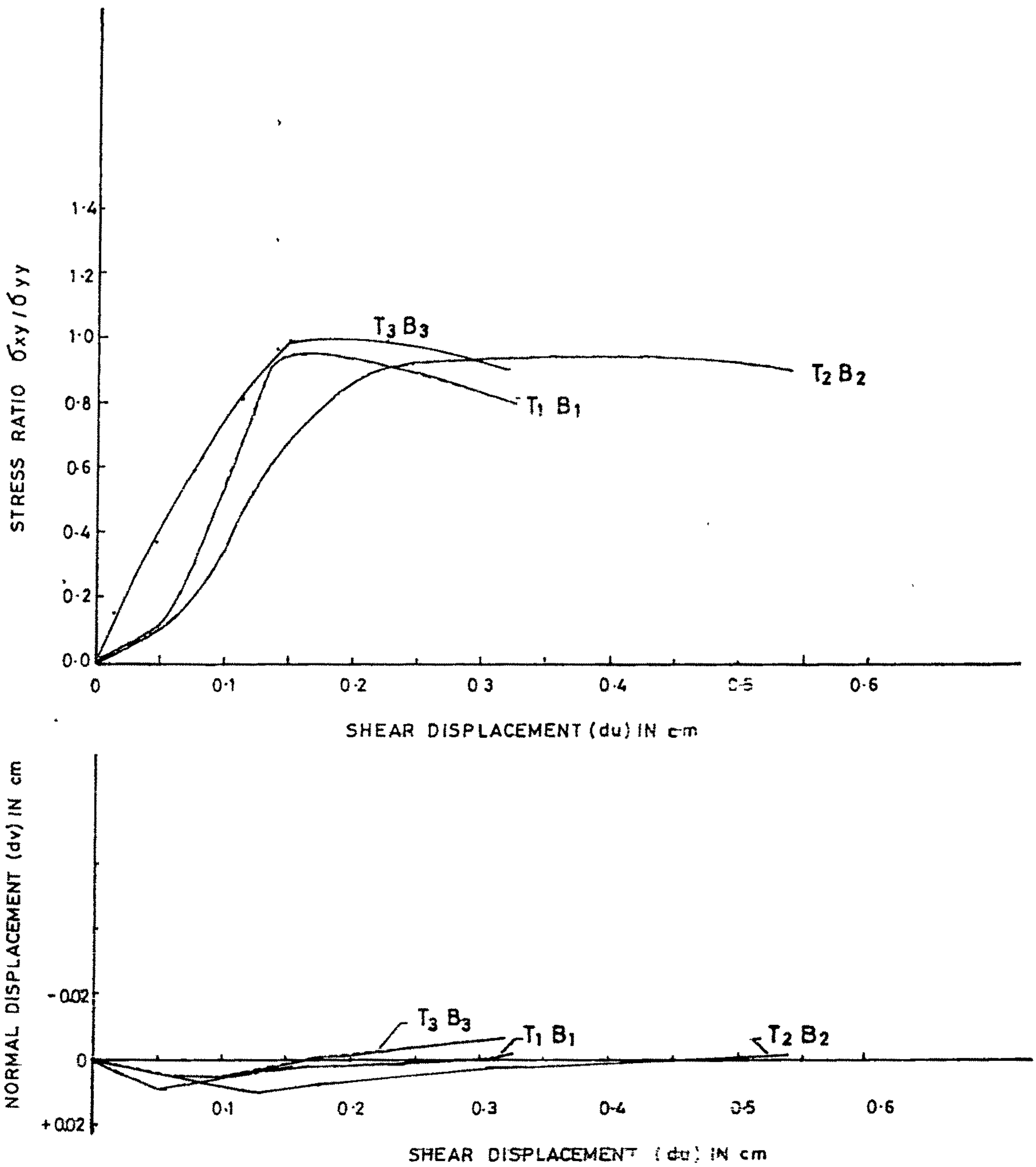


FIG: 6·13 RELATION BETWEEN SHEAR STRESS - SHEAR DISPLACEMENT AND NORMAL DISPLACEMENT

- UNLUBRICATED PLANE SURFACE

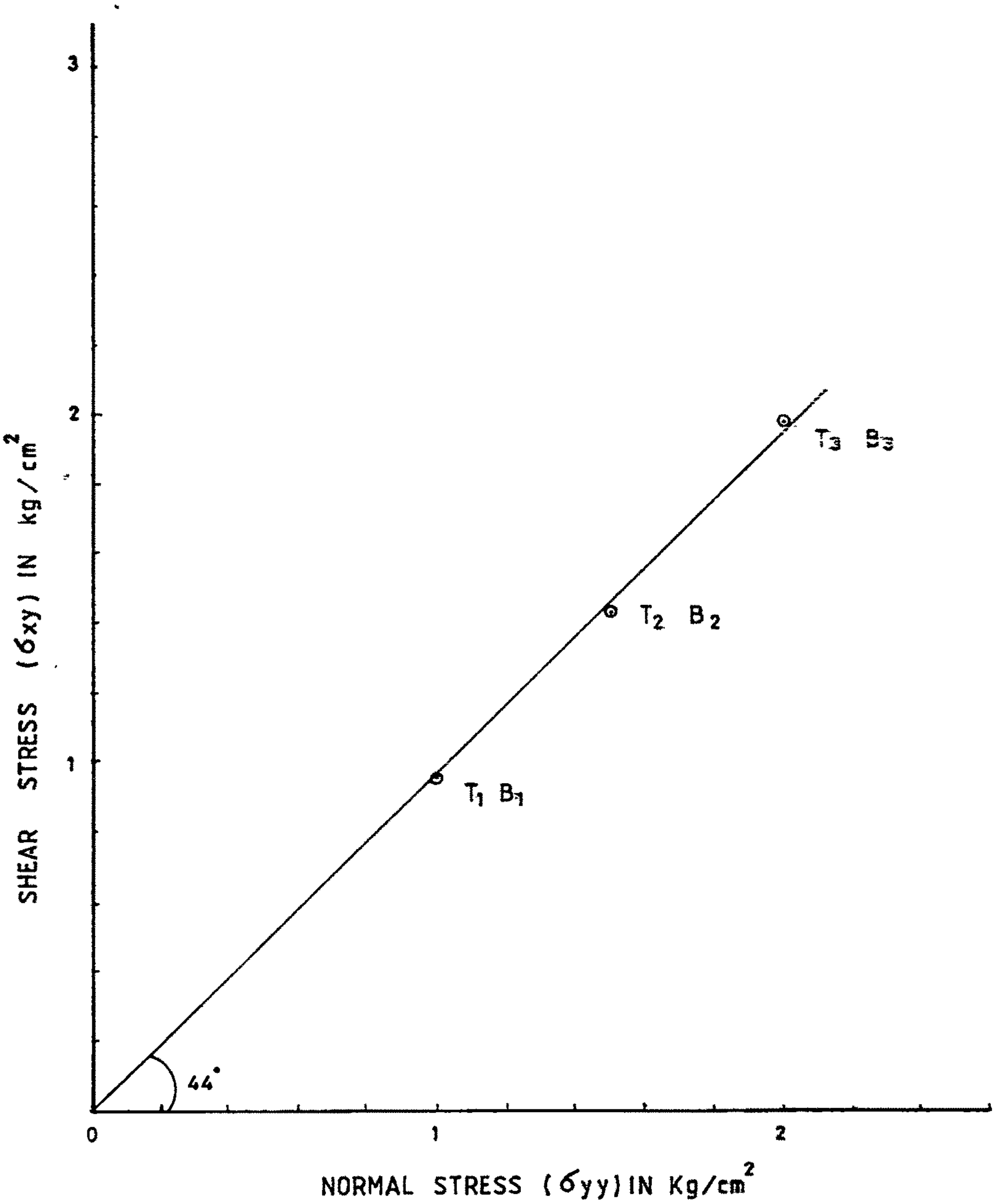


FIG: 6·14 COULOMB PLOT FOR UNLUBRICATED PLANE SURFACES

TABLE 6.4 : SAMPLE OF LUBRICATED PLANE SURFACE

Sample T_4B_4 Normal Stress $= \sigma_{yy} = 1.0$ kg/cm^2 (constant)

Sr. No.	Shear stress 'σxy' in kg/cm^2	Normal displacement 'dv' in cm	Shear displacement 'du' in cm
1	2	3	4
1	0.18	0.001	0.017
2	0.35	0.001	0.047
3	0.32	0.001	0.077
4	0.28	0.001	0.132
5	0.28	0.001	0.242
6	0.28	0.001	0.342
7	0.28	0.001	0.477
8	0.25	0.001	0.597
9	0.18	0.001	0.817

TABLE 6.5 : SAMPLE OF LUBRICATED PLANE SURFACE

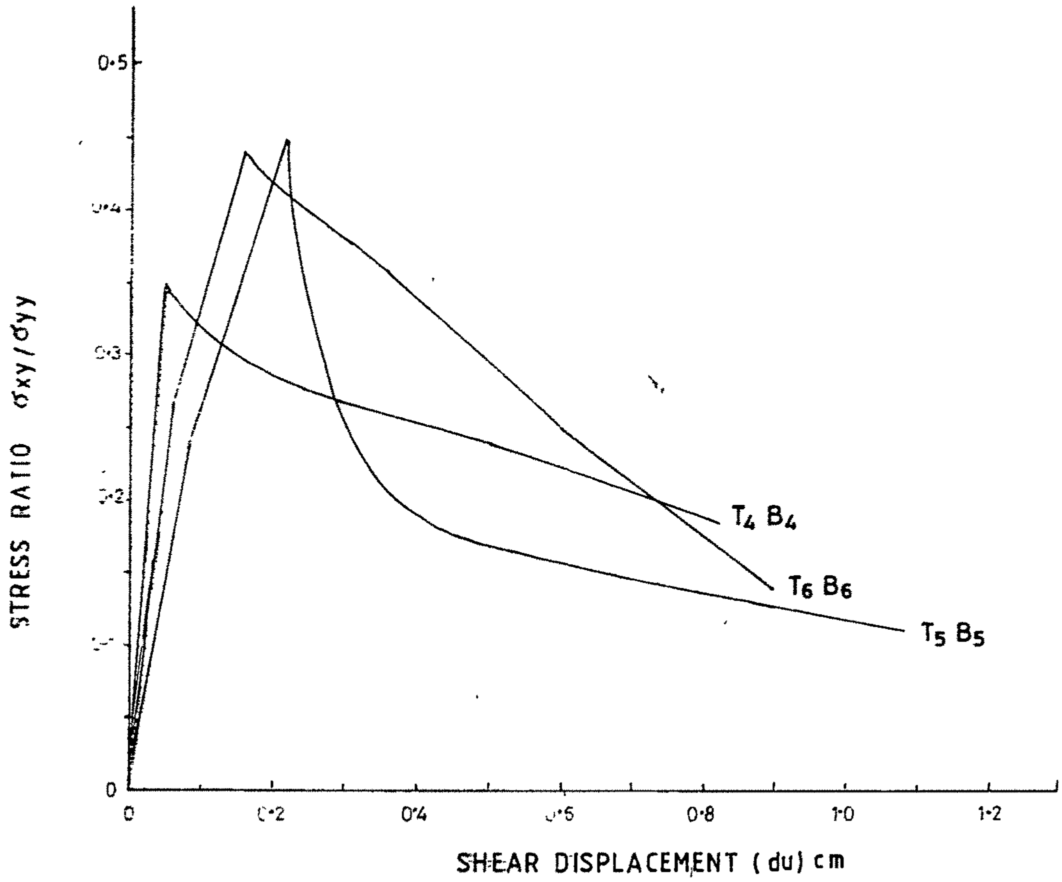
Sample T_5B_5 Normal Stress $= \sigma yy = 1.5$ kg/cm^2 (constant)

Sr. No.	Shear stress 'σxy' in kg/cm^2	Normal displacement 'dv' in cm	Shear displacement 'du' in cm
1	2	3	4
1	0.07	0.005	0.025
2	0.14	0.005	0.031
3	0.21	0.006	0.038
4	0.28	0.006	0.047
5	0.35	0.007	0.063
6	0.42	0.008	0.078
7	0.42	0.008	0.085
8	0.42	0.008	0.095
9	0.43	0.008	0.113
10	0.43	0.008	0.150
11	0.58	0.008	0.200
12	0.68	0.009	0.220
13	0.40	0.010	0.250
14	0.33	0.011	0.275
15	0.28	0.014	0.350
16	0.25	0.015	0.400
17	0.24	0.015	0.450
18	0.24	0.015	0.500
19	0.23	0.017	0.620
20	0.21	0.017	0.700
21	0.21	0.017	0.800
22	0.21	0.019	0.900
23	0.19	0.020	1.000
24	0.18	0.020	1.080

TABLE 6.6 : SAMPLE OF LUBRICATED PLANE SURFACE

Sample T_6B_6 Normal Stress = σ_{yy} = 2.0 kg/cm^2 (constant)

Sr. No.	Shear stress 'σ_{xy}' in kg/cm^2	Normal displacement 'dv' in cm	Shear displacement 'du' in cm
1	2	3	4
1	0.18	0.003	0.005
2	0.35	0.004	0.015
3	0.53	0.004	0.057
4	0.71	0.006	0.142
5	0.88	0.009	0.155
6	0.71	0.009	0.362
7	0.71	0.010	0.457
8	0.63	0.011	0.497
9	0.35	0.012	0.687
10	0.32	0.012	0.917



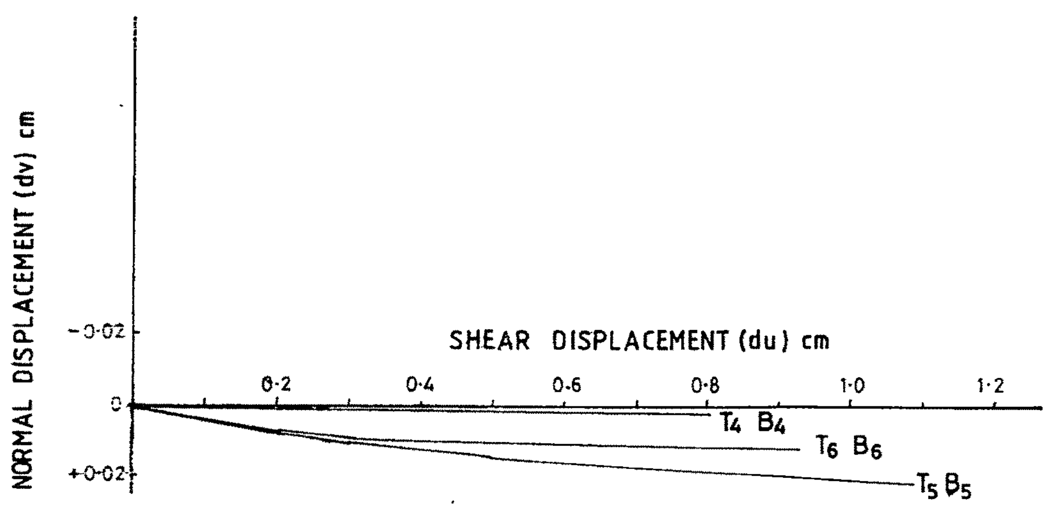


FIG: 6·15 RELATION BETWEEN SHEAR STRESS SHEAR DISPLACEMENT AND NORMAL DISPLACEMENT

– LUBRICATED PLANE SURFACES

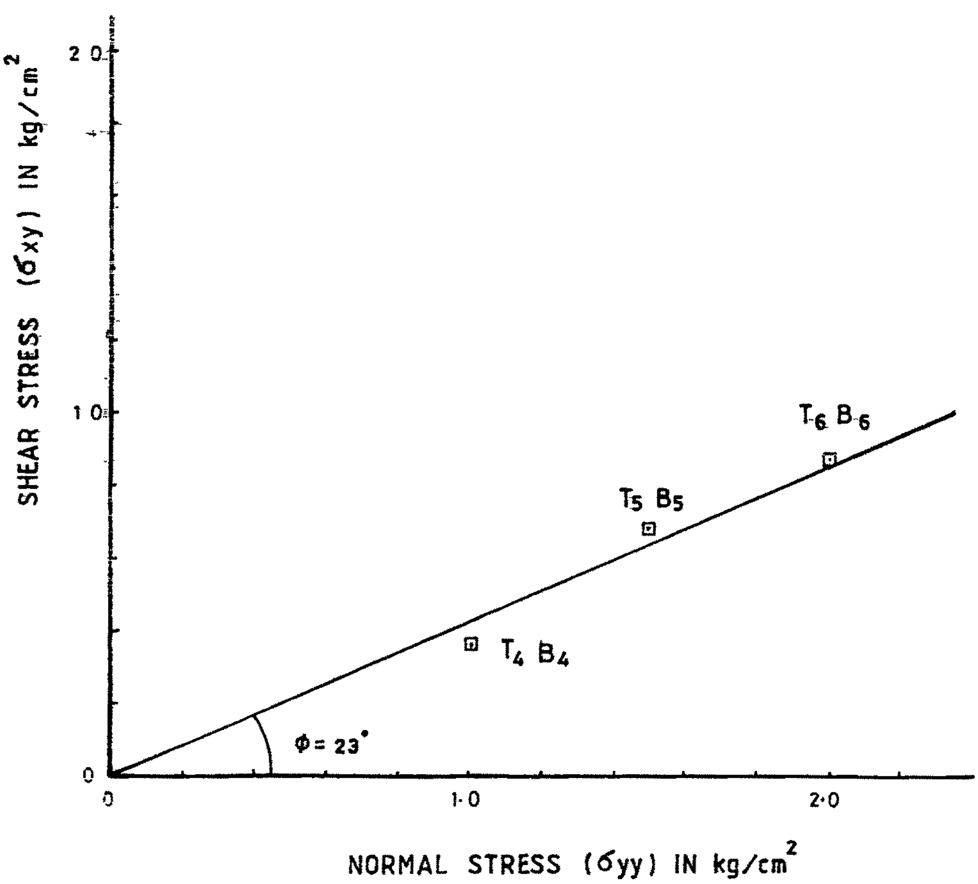


FIG: 6.16 COULOMB PLOT FOR LUBRICATED PLANE SURFACES

TABLE 6.7 : SAMPLE OF REGULARLY ASPIRATED SURFACE

Sample T_7B_7 Normal Stress = σyy = 1.0 kg/cm^2 (constant)

Sr. No.	Shear stress 'σxy' in kg/cm^2	Normal displacement 'dv' in cm	Shear displacement 'du' in cm
1	2	3	4
1	0.15	0	0.020
2	0.88	0	0.079
3	1.03	-0.001	0.093
4	1.18	-0.003	0.110
5	1.33	-0.008	0.129
6	1.44	-0.015	0.153
7	1.47	-0.018	0.172
8	1.54	-0.032	0.208
9	1.62	-0.048	0.256
10	1.73	-0.058	0.283
11	1.77	-0.070	0.324
12	1.92	-0.082	0.373
13	2.06	-0.112	0.463
14	2.26	-0.115	0.481
15	2.36	-0.118	0.500
			contd...

Table 6.7 (contd...)

1	2	3	4
16	2.50	-0.135	0.548
17	2.41	-0.148	0.581
18	2.36	-0.161	0.613
19	2.36	-0.184	0.677
20	2.30	-0.196	0.703
21	2.26	-0.219	0.761
22	2.21	-0.231	0.793
23	2.06	-0.257	0.860
24	1.92	-0.264	0.879
25	1.77	-0.269	0.893
26	1.62	-0.276	0.913
27	1.47	-0.281	0.936
28	1.33	-0.284	0.971
29	1.18	-0.284	1.013
30	0.59	-0.265	1.169

TABLE 6.8 : SAMPLE OF REGULARLY ASPIRATED SURFACE

Sample T_8B_8 Normal Stress = σyy = 1.5 kg/cm^2 (constant)

Sr. No.	Shear stress 'σxy' in kg/cm^2	Normal displacement 'dv' in cm	Shear displacement 'du' in cm
1	2	3	4
1	0.15	0.004	0.012
2	0.44	0.004	0.037
3	0.59	0.005	0.053
4	1.03	0.005	0.090
5	1.47	0.005	0.131
6	2.21	0.005	0.189
7	2.36	0.003	0.208
8	2.51	-0.006	0.232
9	2.65	-0.014	0.267
10	2.80	-0.049	0.357
11	2.95	-0.086	0.472
12	3.10	-0.101	0.514
13	3.24	-0.110	0.550
14	3.33	-0.122	0.580
15	3.10	-0.130	0.610
			contd...

Table 6.8 (contd...)

1	2	3	4
16	2.95	-0.152	0.680
17	2.80	-0.188	0.798
18	2.65	-0.200	0.835
19	2.51	-0.213	0.875
20	2.36	-0.224	0.913
21	2.21	-0.230	0.945
22	2.06	-0.234	0.970
23	1.92	-0.237	0.998
24	1.77	-0.239	1.016
25	1.62	-0.240	1.038
26	1.47	-0.240	1.055
27	1.18	-0.233	1.115
28	1.03	-0.221	1.167
29	0.88	-0.200	1.259
30	0.80	-0.168	1.357
31	0.74	-0.145	1.420
32	0.70	-0.120	1.485
33	0.65	-0.093	1.585

TABLE 6.9 : SAMPLE OF REGULARLY ASPIRATED SURFACE

Sample T_9B_9 Normal Stress = σyy = 2.0 kg/cm^2 (constant)

Sr. No.	Shear stress 'σxy' in kg/cm^2	Normal displacement 'dv' in cm	Shear displacement 'du' in cm
1	2	3	4
1	0.15	0.006	0.041
2	0.59	0.006	0.065
3	0.74	0.007	0.074
4	1.47	0.007	0.126
5	1.62	0.006	0.138
6	1.77	0.005	0.152
7	1.92	0.001	0.164
8	2.06	-0.001	0.176
9	2.21	-0.002	0.187
10	2.36	-0.002	0.198
11	2.51	-0.003	0.211
12	2.65	-0.003	0.225
13	2.80	-0.004	0.244
14	2.95	-0.005	0.260
15	3.10	-0.007	0.275
16	3.24	-0.009	0.292
17	3.39	-0.016	0.347
18	3.54	-0.038	0.411
19	3.69	-0.046	0.452
20	3.83	-0.052	0.482
21	3.98	-0.056	0.503

contd...

Table 6.9 (contd...)

1	2	3	4
22	4.13	-0.067	0.557
23	4.28	-0.074	0.581
24	4.36	-0.081	0.610
25	4.24	-0.098	0.645
26	4.09	-0.101	0.651
27	3.97	-0.109	0.679
28	3.83	-0.114	0.709
29	3.69	-0.151	0.709
30	3.54	-0.167	0.770
31	3.39	-0.174	0.789
32	3.24	-0.182	0.818
33	3.10	-0.190	0.855
34	2.95	-0.194	0.871
35	2.80	-0.197	0.884
36	2.65	-0.200	0.910
37	2.51	-0.202	0.917
38	2.36	-0.204	0.943
39	2.21	-0.206	0.972
40	2.06	-0.207	0.996
41	1.92	-0.207	1.021
42	1.77	-0.206	1.048
43	1.47	-0.195	1.111
44	1.18	-0.164	1.225
45	1.17	-0.145	1.288

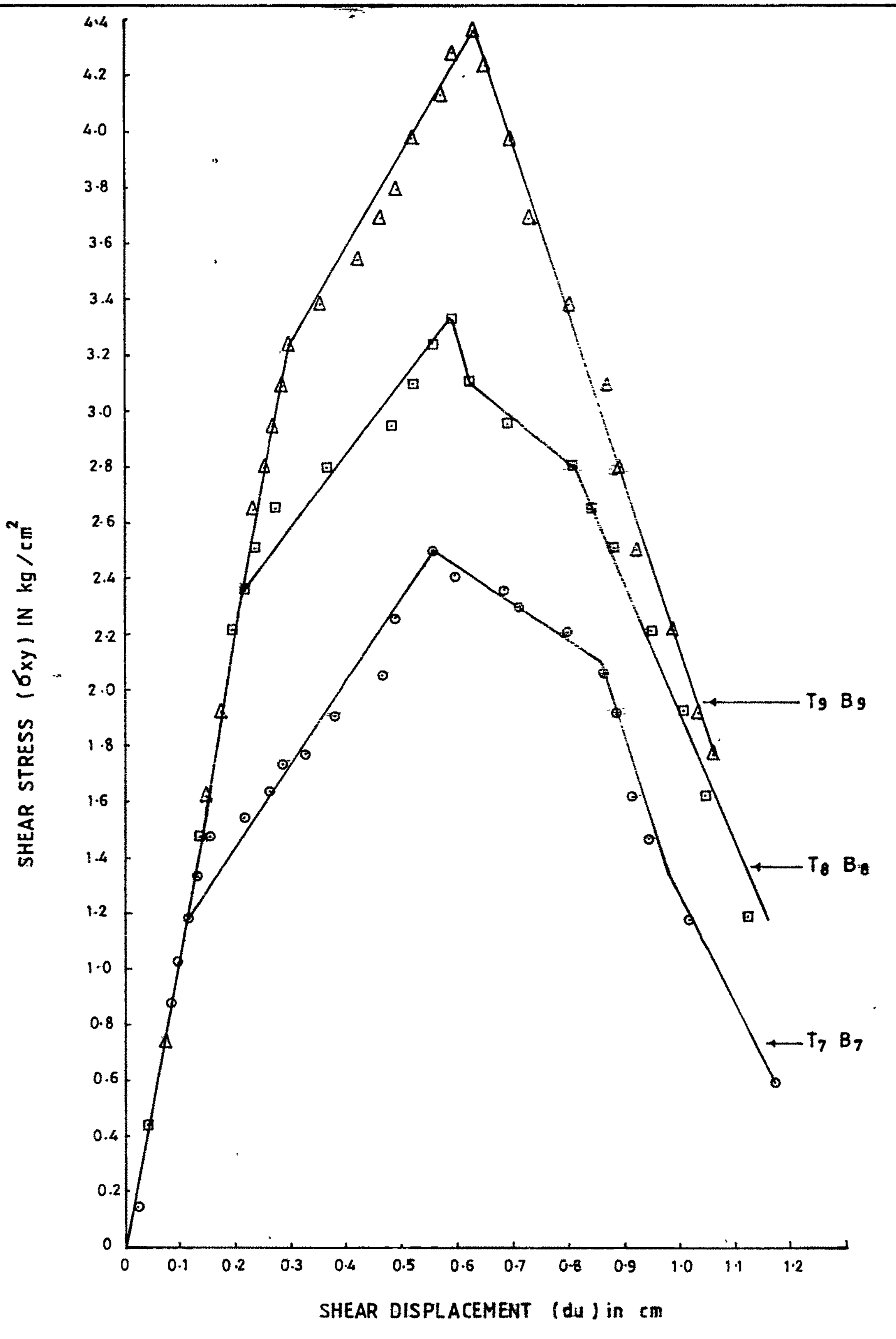


FIG: 6.17 SHEAR STRESS - SHEAR DISPLACEMENT RELATIONSHIP

– REGULARLY ASPIRATED SURFACES

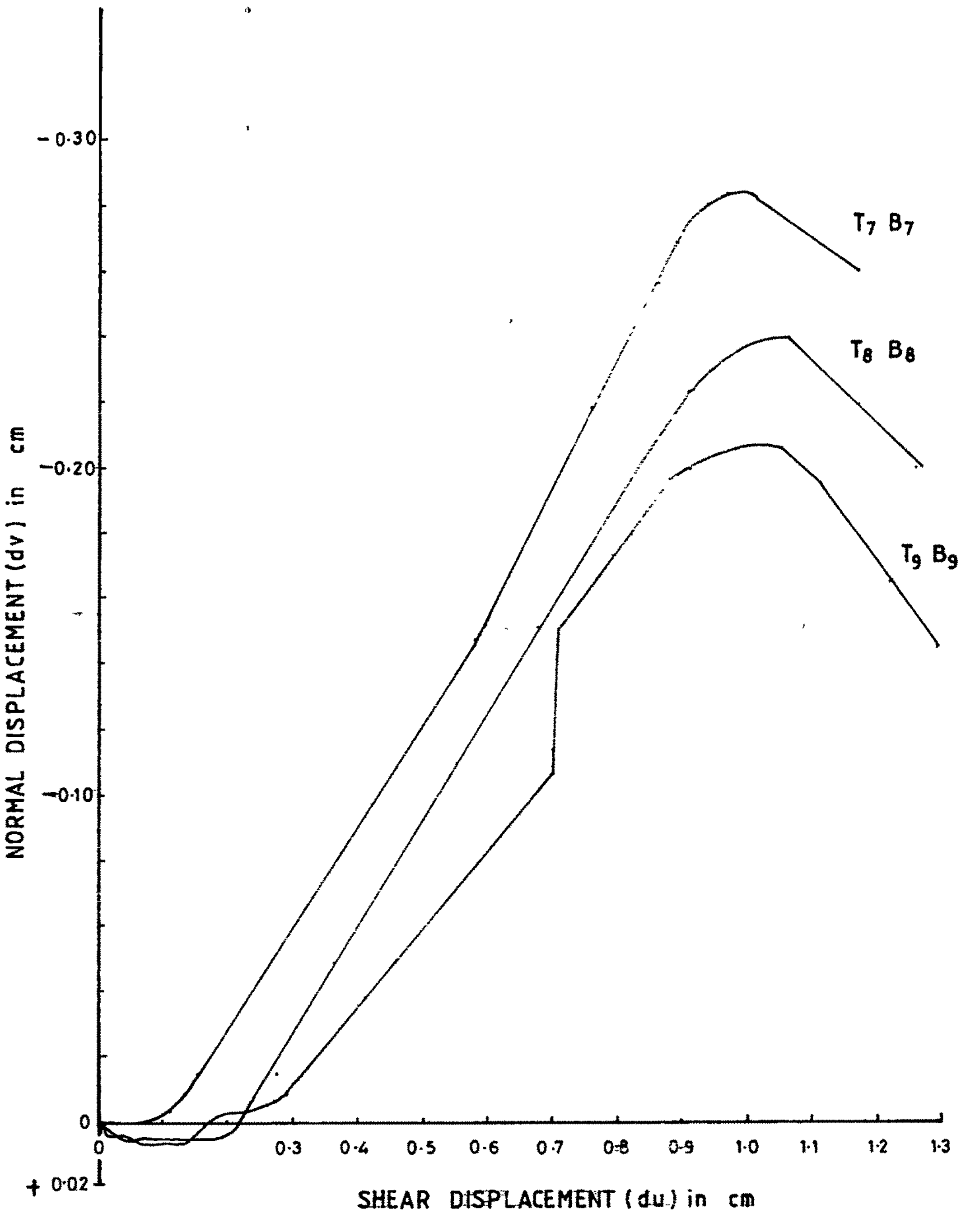


FIG: 6·18 VARIATION OF NORMAL DISPLACEMENT WITH SHEAR DISPLACEMENT

— REGULARLY ASPIRATED SURFACES

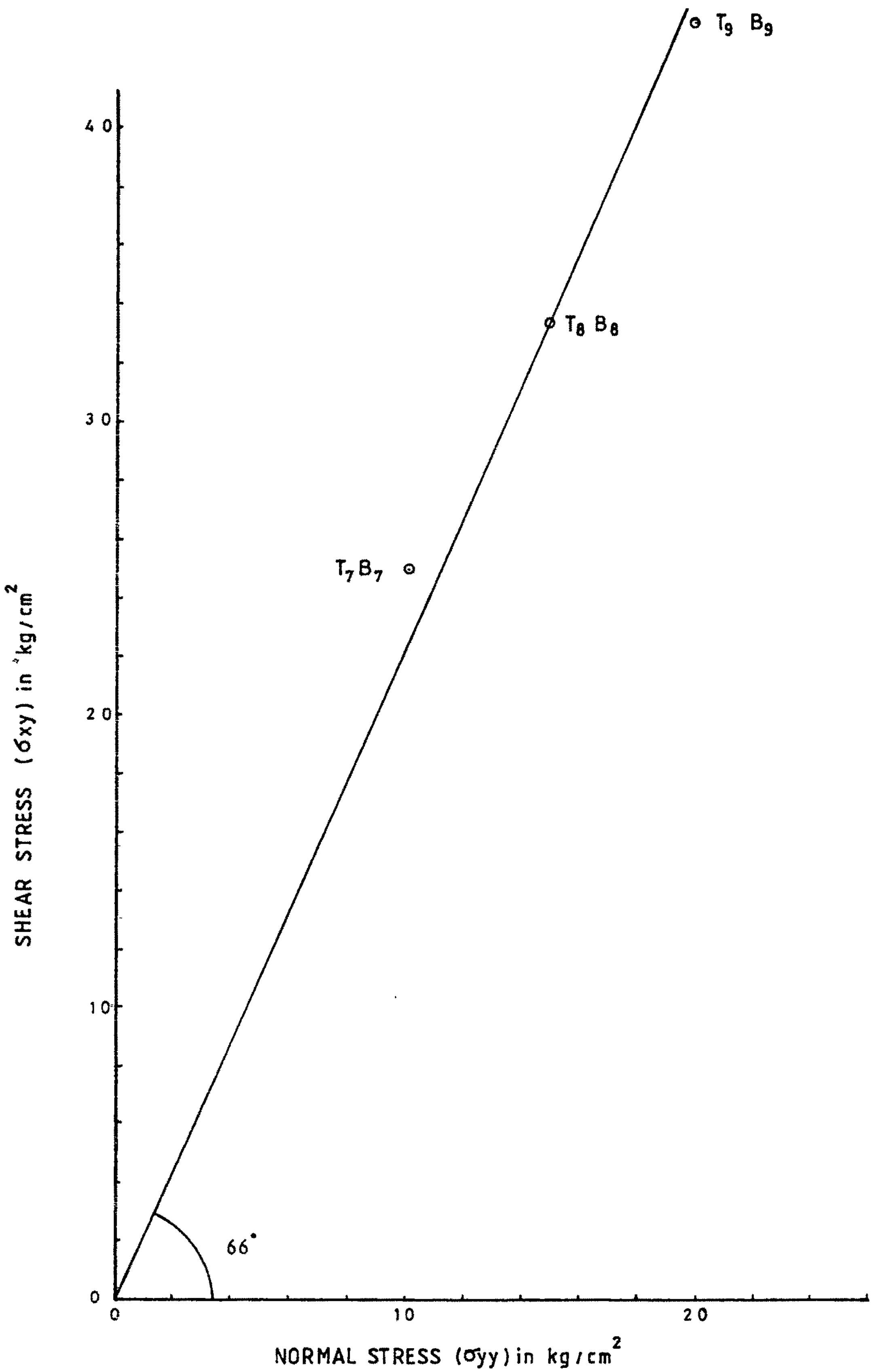


FIG: 6.19 COULOMB PLOT FOR REGULARLY ASPIRATED SURFACES

TABLE 6.10 : SAMPLE OF PLANE SURFACE WITH IRREGULAR ASPERITIES

Sample $T_{10}B_{10}$ Normal Stress = σyy = 1.0 kg/cm^2 (constant)

Sr. No.	Shear stress 'σxy' in kg/cm^2	Normal displacement 'dv' in cm	Shear displacement 'du' in cm
1	2	3	4
1	0.18	0.002	0.021
2	0.35	0.003	0.036
3	0.53	0.005	0.076
4	0.71	0.006	0.111
5	0.88	0.006	0.129
6	1.06	0.006	0.141
7	1.23	0.006	0.159
8	1.31	0.004	0.181
9	1.23	0.001	0.201
10	1.16	0.000	0.276
11	1.06	-0.001	0.298
12	0.99	-0.001	0.406
13	0.92	-0.001	0.441
14	0.85	-0.001	0.491

TABLE 6.11 : SAMPLE OF PLANE SURFACE WITH IRREGULAR ASPERITIES

Sample $T_{11}B_{11}$ Normal Stress = σyy = 1.5 kg/cm^2 (constant).

Sr. No.	Shear stress 'σxy' in kg/cm^2	Normal displacement 'dv' in cm	Shear displacement 'du' in cm
1	2	3	4
1	0.18	0.000	0.003
2	0.35	0.002	0.008
3	0.53	0.006	0.048
4	0.71	0.009	0.098
5	0.88	0.010	0.121
6	1.06	0.011	0.138
7	1.23	0.013	0.153
8	1.41	0.013	0.171
9	1.59	0.014	0.185
10	1.76	0.014	0.223
11	1.83	0.013	0.263
12	1.66	0.014	0.283
13	1.59	0.015	0.303
14	1.41	0.016	0.493
15	1.23	0.017	0.638

TABLE 6.12 : SAMPLE OF PLANE SURFACE WITH IRREGULAR ASPERITIES

Sample $T_{12}B_{12}$ Normal Stress = σyy = 2.0 kg/cm^2 (constant)

Sr. No.	Shear stress 'σxy' in kg/cm^2	Normal displacement 'dv' in cm	Shear displacement 'du' in cm
1	2	3	4
1	0.07	0.000	0.007
2	0.14	0.001	0.011
3	0.21	0.002	0.017
4.	0.28	0.002	0.023
5	0.35	0.002	0.032
6	0.42	0.002	0.041
7	0.49	0.003	0.050
8	0.56	0.003	0.056
9	0.63	0.003	0.060
10	0.68	0.003	0.065
11	0.77	0.003	0.071
12	0.84	0.003	0.076
13	0.91	0.003	0.083
14	0.98	0.002	0.091
15	1.03	0.002	0.097
16	1.09	0.002	0.109
17	1.16	0.000	0.128
18	1.20	-0.001	0.145
19	1.23	-0.001	0.149
20	1.30	-0.001	0.155
21	1.37	-0.001	0.162
22	1.44	-0.001	0.170
23	1.50	-0.001	0.176
24	1.57	-0.001	0.182
25	1.64	-0.001	0.186
26	1.71	-0.001	0.191
27	1.78	-0.001	0.196
			contd...

Table 6.12 (contd...)

1	2	3	4
28	1.85	-0.001	0.200
29	1.91	-0.002	0.205
30	1.98	-0.002	0.210
31	2.05	-0.002	0.214
32	2.12	-0.002	0.220
33	2.19	-0.002	0.224
34	2.26	-0.003	0.228
35	2.33	-0.003	0.234
36	2.40	-0.003	0.239
37	2.46	-0.003	0.243
38	2.53	-0.003	0.248
39	2.60	-0.004	0.252
40	2.67	-0.004	0.256
41	2.74	-0.004	0.261
42	2.46	-0.004	0.265
43	2.53	-0.004	0.275
44	2.57	-0.004	0.280
45	2.19	-0.004	0.287
46	2.22	-0.004	0.299
47	2.20	-0.004	0.310
48	2.18	-0.007	0.330
49	2.46	-0.008	0.400
50	2.36	-0.010	0.500

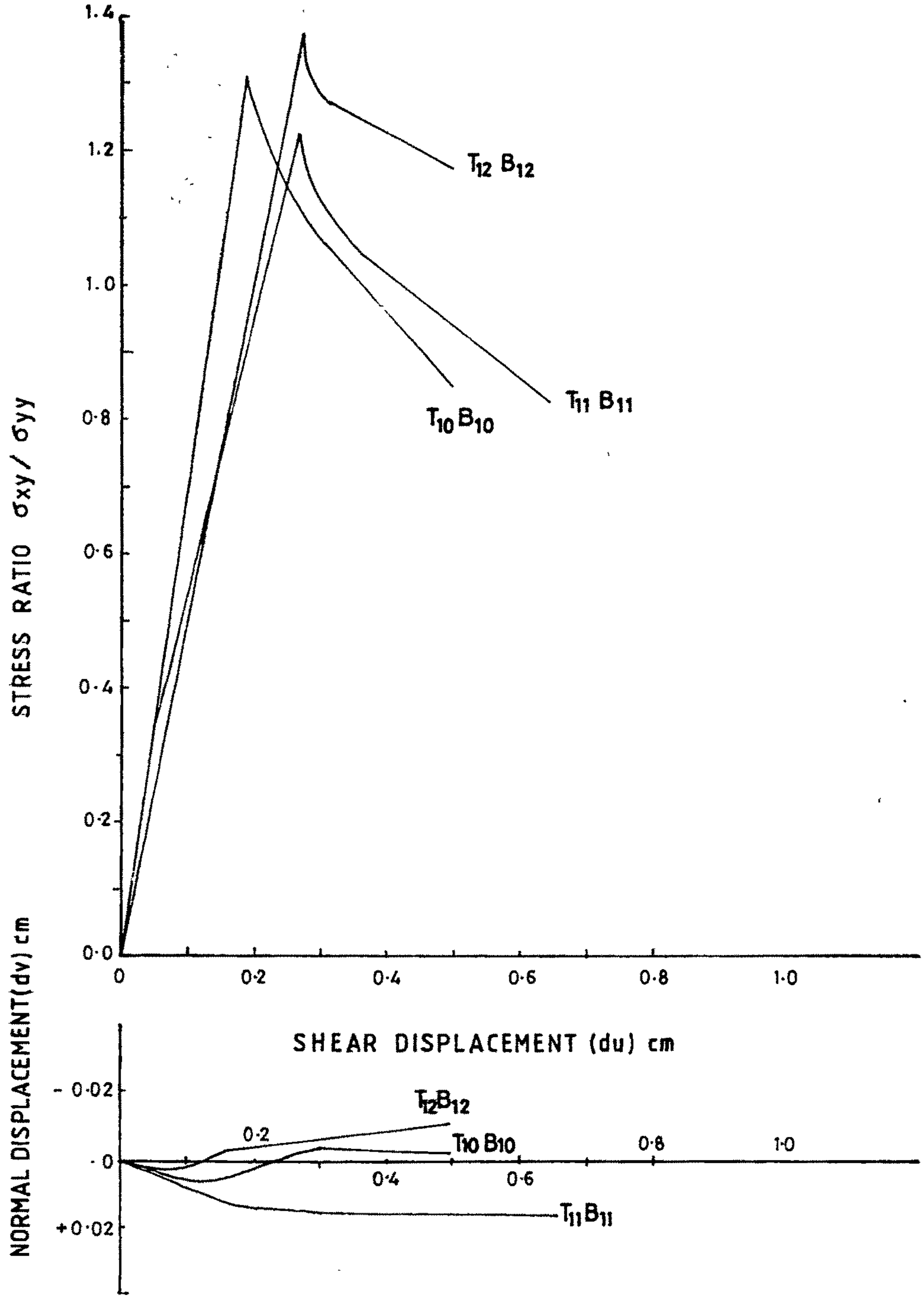


FIG: 6·20 RELATION BETWEEN SHEAR STRESS-SHEAR DISPLACEMENT AND NORMAL DISPLACEMENT

– PLANE SURFACES WITH IRREGULAR ASPERITIES

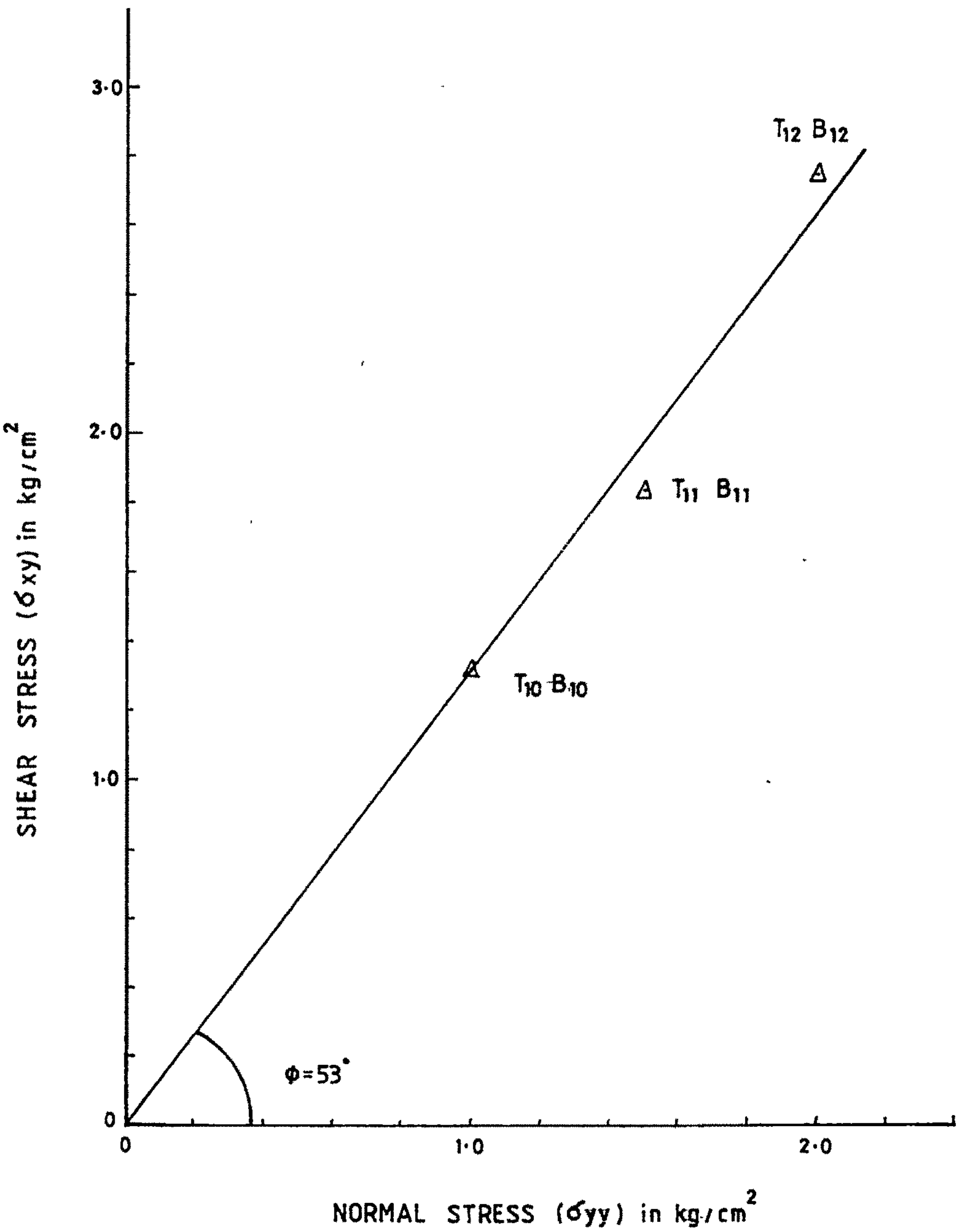


FIG: 6·21 COULOMB PLOT FOR PLANE SURFACES WITH IRREGULAR ASPERITIES

6.3.6 Observations of tests conducted on gouged plane surfaces are given in Table 6.13 to 6.15. Fig. 6.22 shows variation of shear stress (σxy) against shear displacement (du) and relation between normal displacement (dv) and shear displacement (du). Coulomb plot is presented in Fig. 6.23.

6.3.7 Following inferences can be drawn from the observations of test data and relevant plots referred to above.

(i) Apparent basic friction angle of the unlubricated plane surfaces (Fig. 6.14) is 44°. However Fig. 6.13 indicates that micro asperities having an asperity angle of about 2° are present on these surfaces and hence the real basic friction angle Ø should be 42°.

(ii) No volume change or dilation occurs during shearing of unlubricated plane surfaces till the peak shear strength is generated. (Fig. 6.13)

(iii) On lubricating the sliding surfaces with grease, the sliding resistance reduces considerably to 23° (Fig. 6.16).

(iv) Lubricated surfaces do not show any volume change or dilation whatsoever (Fig. 6.15).

(v) Shear stiffness of unlubricated surfaces is 10.0 kg/cm^3 (Fig. 6.13). This reduces to 5.0 kg/cm^3 (Fig. 6.15) on lubricating the surfaces.

(vi) Regularly aspirated surfaces having angle of asperity equal to 25° exhibit a frictional resistance equivalent to 66° (Fig. 6.19). This is almost equal to summation of basic friction angle Ø and angle of asperity i.e. 42 + 25 = 67°.

TABLE 6.13 : SAMPLE OF GOUGED PLANE SURFACE

Sample $T_{13}B_{13}$ Normal Stress = σyy = 1.0 kg/cm^2 (constant)

Sr. No.	Shear stress 'σxy' in kg/cm^2	Normal displacement 'dv' in cm	Shear displacement 'du' in cm
1	2	3	4
1	0.07	0.003	0.009
2	0.14	0.004	0.015
3	0.21	0.005	0.023
4	0.28	0.006	0.034
5	0.34	0.010	0.050
6	0.35	0.012	0.064
7	0.39	0.013	0.085
8	0.32	0.013	0.100
9	0.29	0.014	0.125
10	0.26	0.014	0.150
11	0.24	0.013	0.175
12	0.23	0.013	0.200
13	0.22	0.013	0.225
14	0.21	0.013	0.250
15	0.21	0.013	0.275
16	0.21	0.014	0.300
17	0.18	0.014	0.400
18	0.18	0.013	0.500
19	0.18	0.013	0.600
20	0.19	0.013	0.700
21	0.20	0.012	0.800
22	0.20	0.012	0.900
23	0.20	0.013	0.900
24	0.20	0.013	1.000
25	0.19	0.012	1.100
26	0.19	0.012	1.200

TABLE 6.14 : SAMPLE OF GOUGED PLANE SURFACE

Sample $T_{14}B_{14}$ Normal Stress = σyy = 1.5 kg/cm^2 (constant)

Sr. No.	Shear stress 'σxy' in kg/cm^2	Normal displacement 'dv' in cm	Shear displacement 'du' in cm
1	2	3	4
1	0.07	0.006	0.015
2	0.14	0.007	0.030
3	0.21	0.007	0.038
4	0.28	0.007	0.055
5	0.35	0.005	0.069
6	0.42	0.005	0.081
7	0.48	0.005	0.098
8	0.48	0.006	0.110
9	0.45	0.008	0.125
10	0.36	0.012	0.200
11	0.26	0.016	0.300
12	0.42	0.021	0.400
13	0.35	0.022	0.500
14	0.33	0.026	0.600
15	0.33	0.029	0.700
16	0.35	0.029	0.800
17	0.35	0.031	0.900
18	0.35	0.032	1.000

TABLE 6.15 : SAMPLE OF GOUGED PLANE SURFACE

Sample $T_{15}B_{15}$ Normal Stress = σyy = 2.0 kg/cm^2 (constant)

Sr. No.	Shear stress 'σxy' in kg/cm^2	Normal displacement 'dv' in cm	Shear displacement 'du' in cm
1	2	3	4
1	0.07	0.001	0.027
2	0.14	0.001	0.035
3	0.21	0.001	0.041
4	0.28	0.001	0.048
5	0.35	0.002	0.055
6	0.42	0.002	0.064
7	0.49	0.002	0.072
8	0.56	0.002	0.079
9	0.63	0.002	0.090
10	0.65	0.005	0.112
11	0.49	0.012	0.200
12	0.52	0.016	0.300
13	0.51	0.017	0.440
14	0.45	0.021	0.540
15	0.43	0.024	0.600
16	0.39	0.024	0.700
17	0.38	0.025	0.800
18	0.38	0.028	0.900
19	0.37	0.028	1.000
20	0.36	0.028	1.100
21	0.35	0.028	1.170

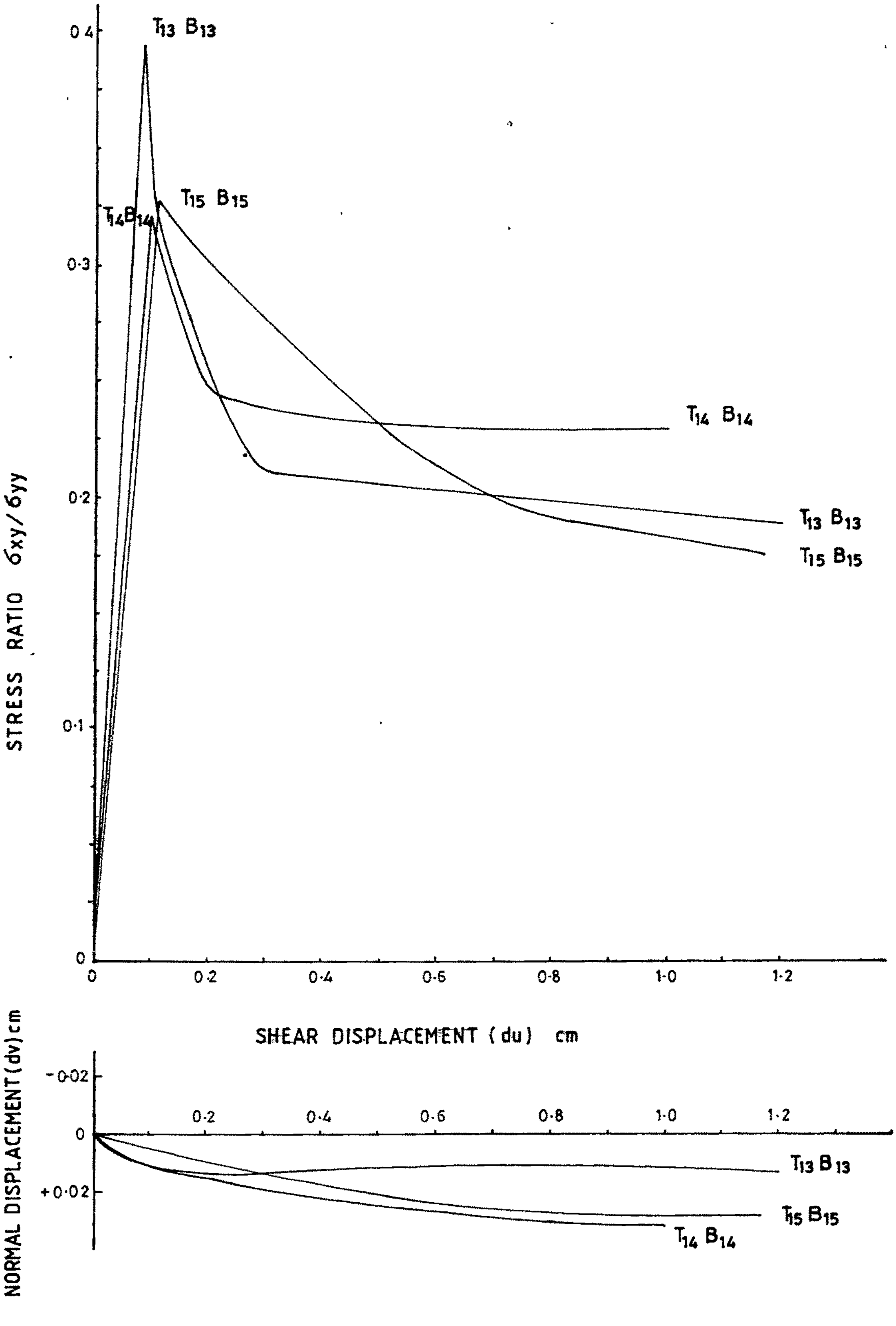


FIG: 6.22 RELATION BETWEEN SHEAR STRESS SHEAR DISPLACEMENT AND NORMAL DISPLACEMENT
-GOUGED PLANE SURFACE

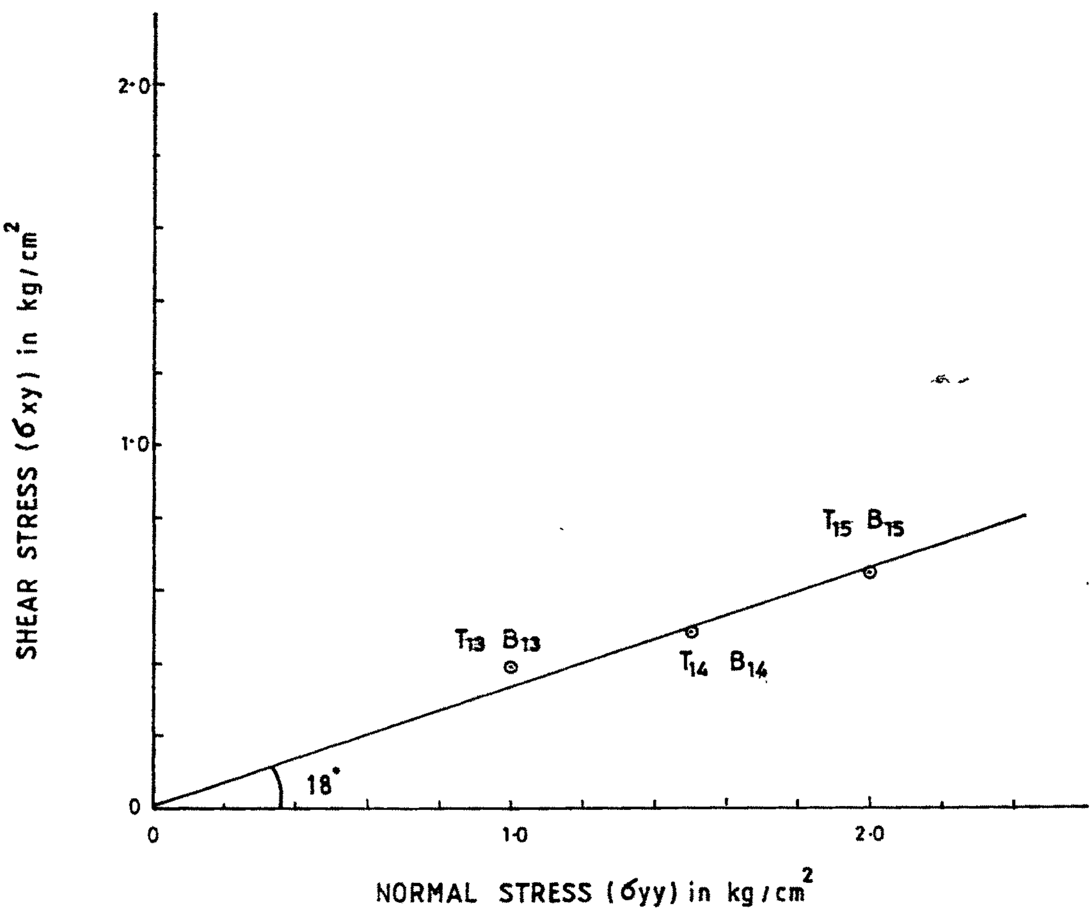


FIG: 6·23 COULOMB PLOT FOR GOUGED PLANE SURFACES

(vii) Regularly aspirated surfaces exhibit a dilation - volume change - during sliding. The average dilation angle ($\tan^{-1} \frac{dv}{du}$) varies from 14° to 18° depending upon the normal stress on the joint surfaces (Fig. 6.18).

(viii) Plane surfaces with irregular asperities exhibit an increase in coefficient of friction beyond that of basic friction (Fig. 6.21). The friction angle becomes 53°. Such surfaces indicate some volume change - dilation -, however, this is very small and irregular (Fig. 6.20).

(ix) Surfaces having a gouge exhibit a drastic reduction in friction resistance. The friction angle becomes 18° (Fig. 6.23).

6.4 CONVENTIONAL DIRECT SHEAR BOX EXPERIMENTS

6.4.1 In addition to the tests conducted for concept verification as stated under para 6.3, observations of direct shear box experiments, as detailed below, conducted by other investigators are utilised for verification of the constitutive relation developed as discussed in para 5.5.1. Saw cut joints were artificially prepared by Dave (1987) in the samples of Basalt rock. These jointed rock samples were tested without gouge and with gouge of cement-sand mortar of different proportions as under :

Designation of sample	Type of joint surface
A2,A4,A6,A8	Without gouge
B2,B4,B6,B8	With gouge of cement-sand mortar of 1:2 proportion.

Designation of sample	Type of joint surface
C1,C2,C4,C8	With gouge of cement-sand mortar of 1:3 proportion
D1,D2,D4,D6	With gouge of cement-sand mortar of 1:4 proportion.

Some selective data from these tests is reproduced and presented as under :

Some typical plots of shear stress (σxy) versus shear displacement (du) and between vertical displacement (dv) and shear displacement (du) for joint surfaces without gouge are reproduced in Fig. 6.24(a) to (c). Similar curves for joint surfaces with gouge are shown in Fig. 6.25(a) to (c). Coulomb plots are presented in Fig. 6.26.

6.5 CYCLIC DIRECT SHEAR BOX EXPERIMENTS

6.5.1 Results of cyclic direct shear box experiments conducted and reported by Shah (1987) are also utilised in verification of the constitutive relation developed, as discussed in para 5.5.1. Saw cut joints in Basalt were filled with gouge of cement-sand mortar of different proportions as under for this investigation.

Designation of sample	Type of joint surface
A1,A2,A4,A6	With gouge of cement-sand mortar of 1:2 proportion
B1,B2,B4,B6	With gouge of cement-sand mortar of 1:3 proportion
C1,C2,C4,C6	With gouge of cement-sand mortar of 1:4 proportion

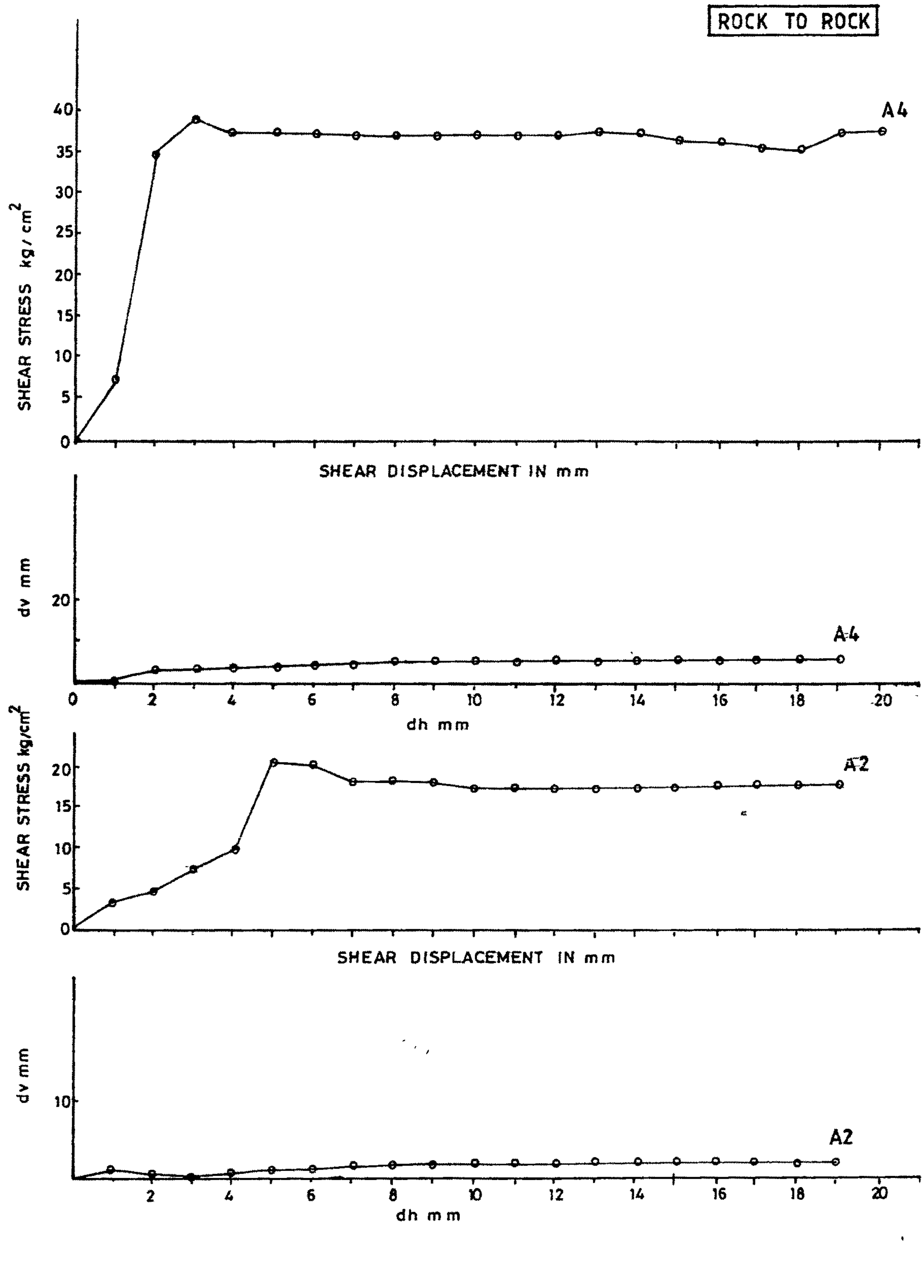


FIG: 6·24(a) SHEAR STRESS - SHEAR DISPLACEMENT - NORMAL DISPLACEMENT RELATIONSHIP

- DAVE (1987)

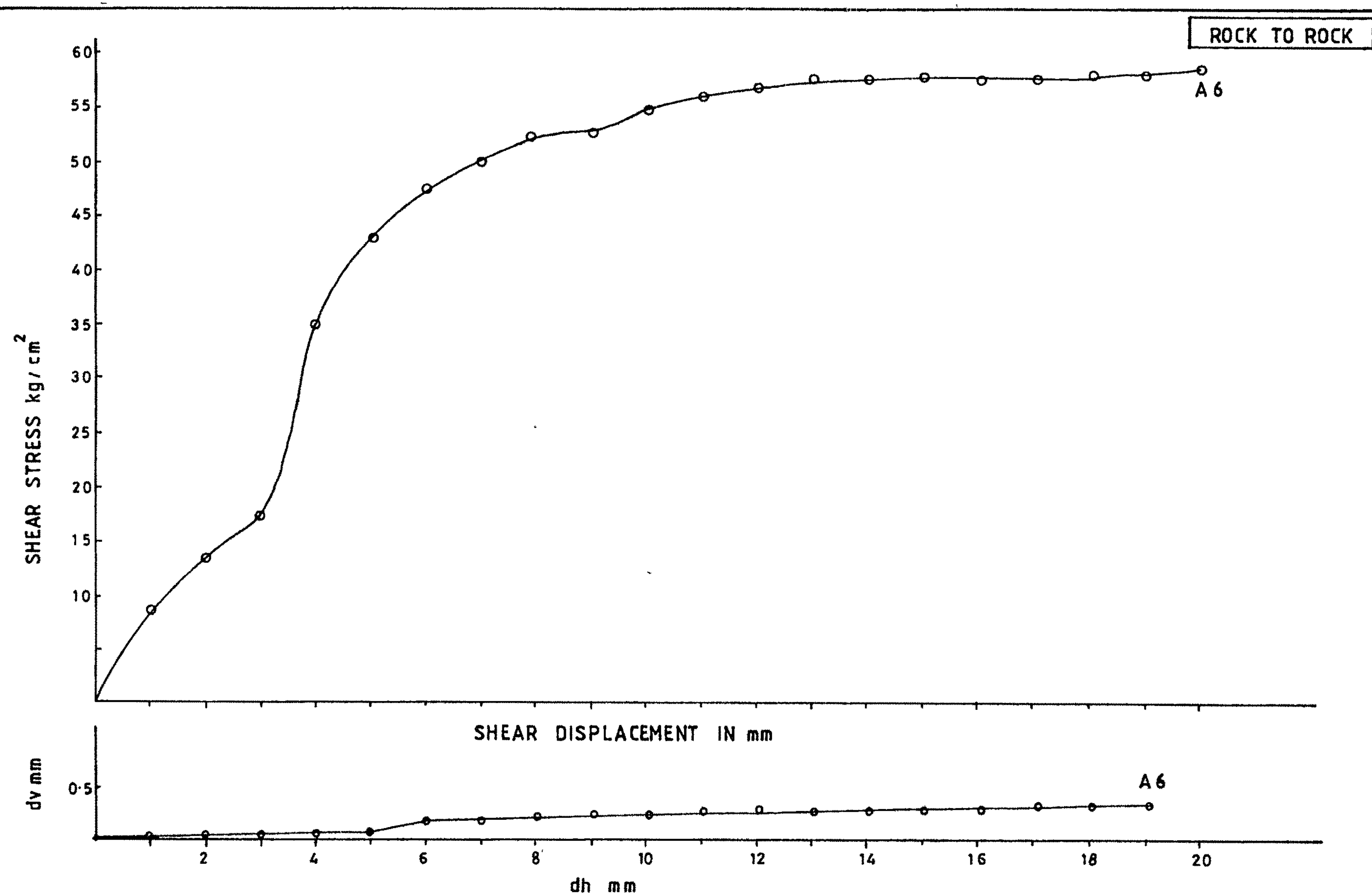


FIG: 6·24(b) SHEAR STRESS - SHEAR DISPLACEMENT - NORMAL DISPLACEMENT RELATIONSHIP - DAVE (1987)

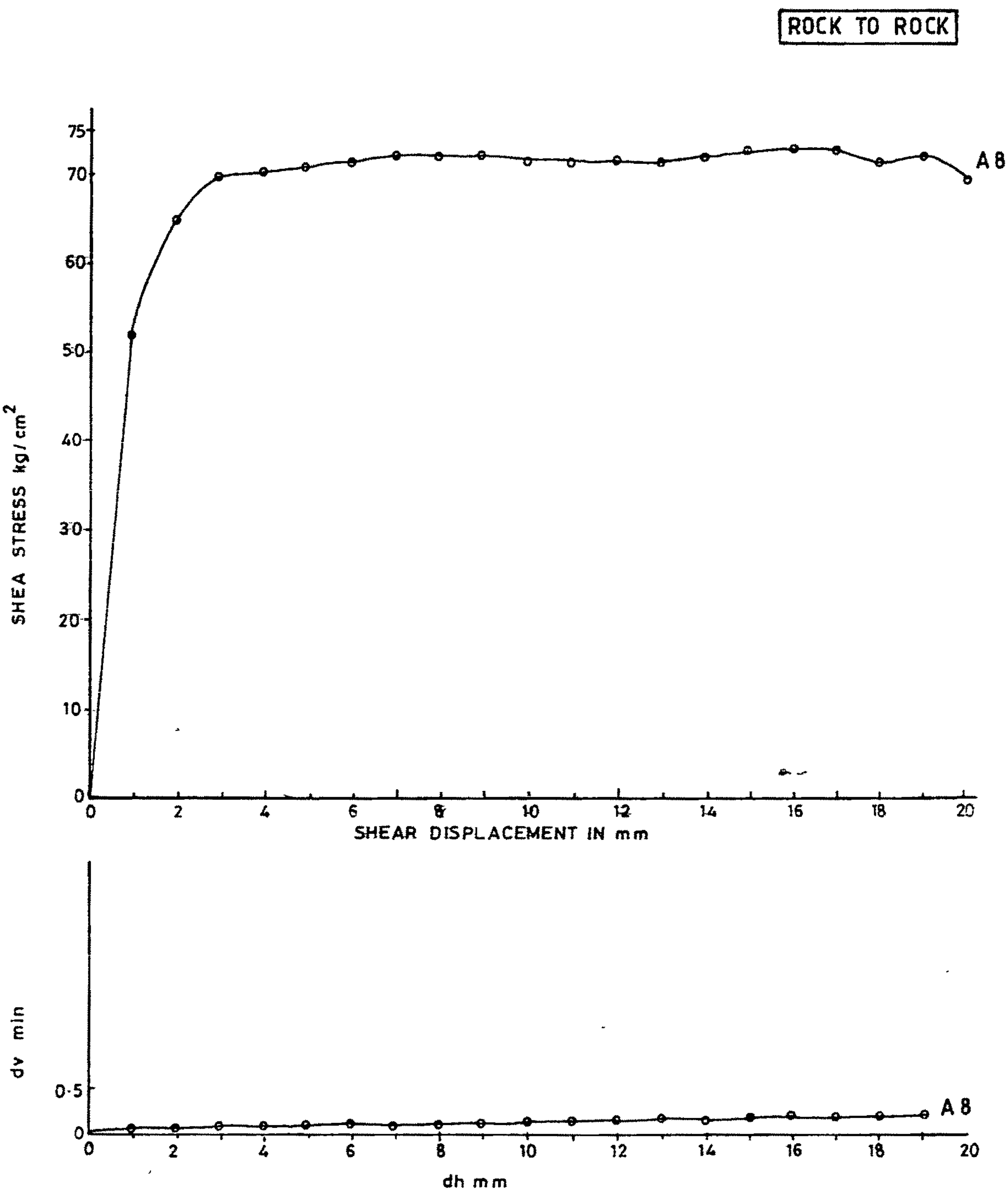


FIG: 6·24 (c) SHEAR STRESS - SHEAR DISPLACEMENT - NORMAL DISPLACEMENT RELATIONSHIP

- DAVE (1987)

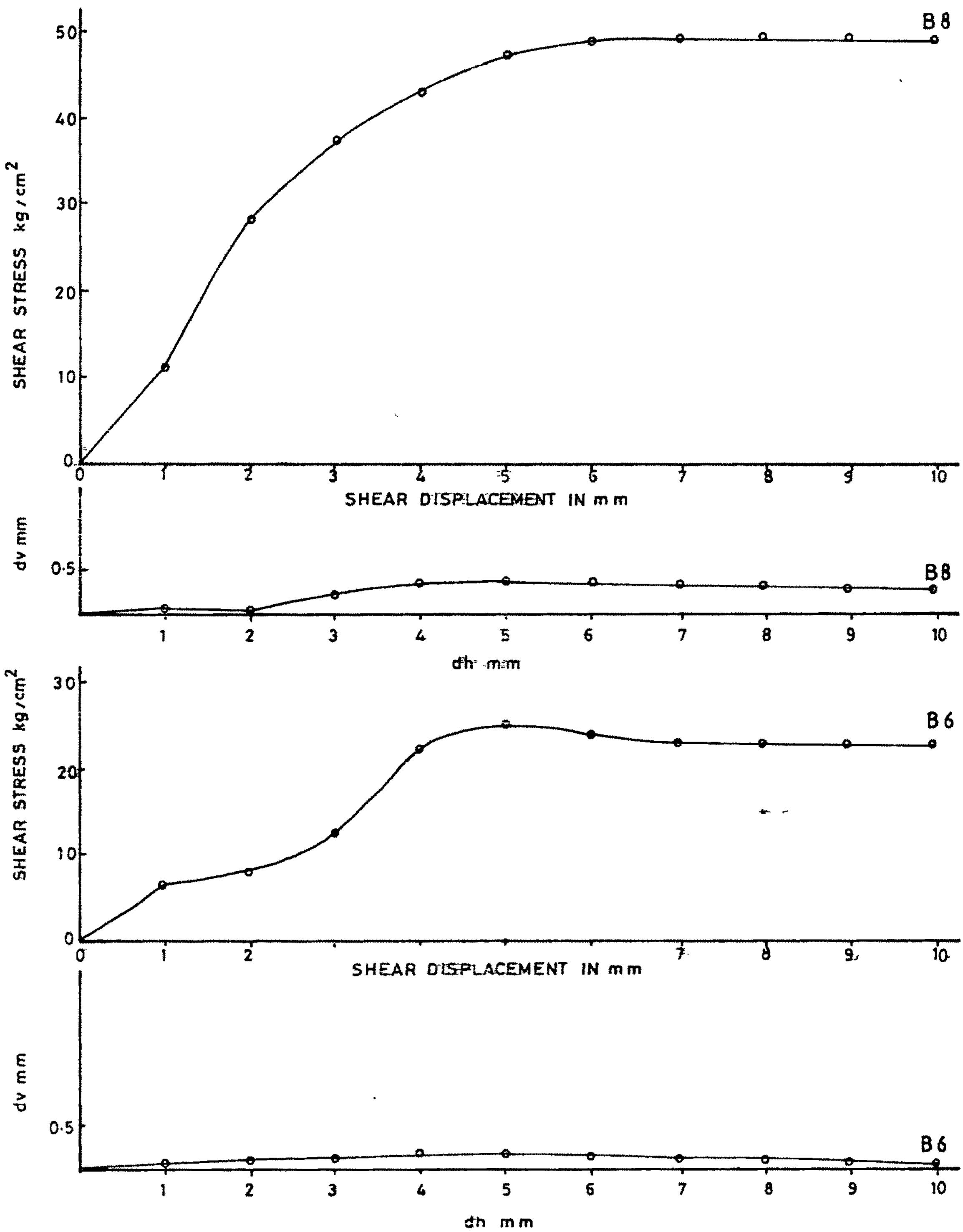


FIG: 6·25(a) SHEAR STRESS - SHEAR DISPLACEMENT - NORMAL DISPLACEMENT RELATIONSHIP

- DAVE (1987)

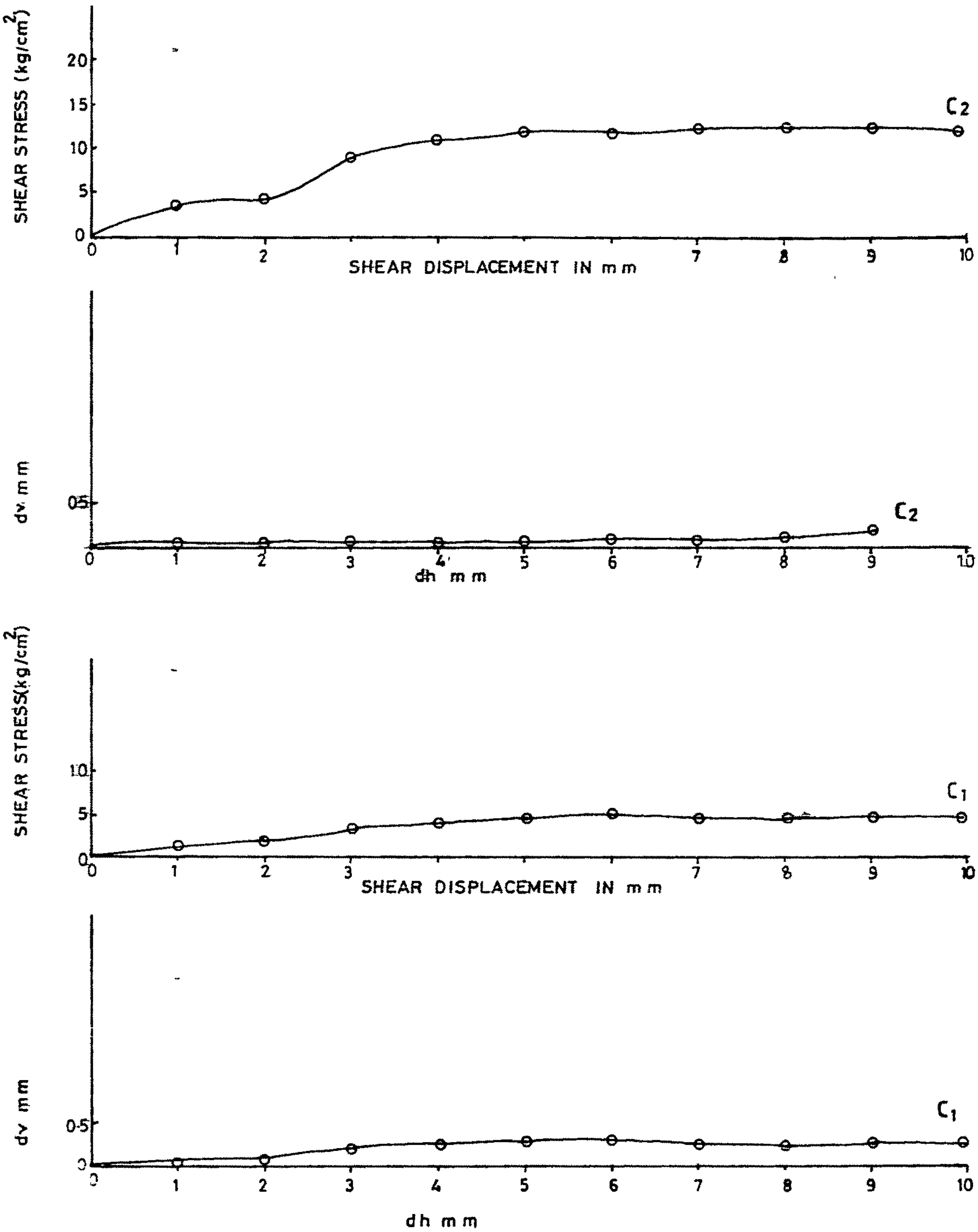


FIG: 6.25(b) SHEAR STRESS- SHEAR DISPLACEMENT- NORMAL DISPLACEMENT RELATIONSHIP

DAVE (1987)

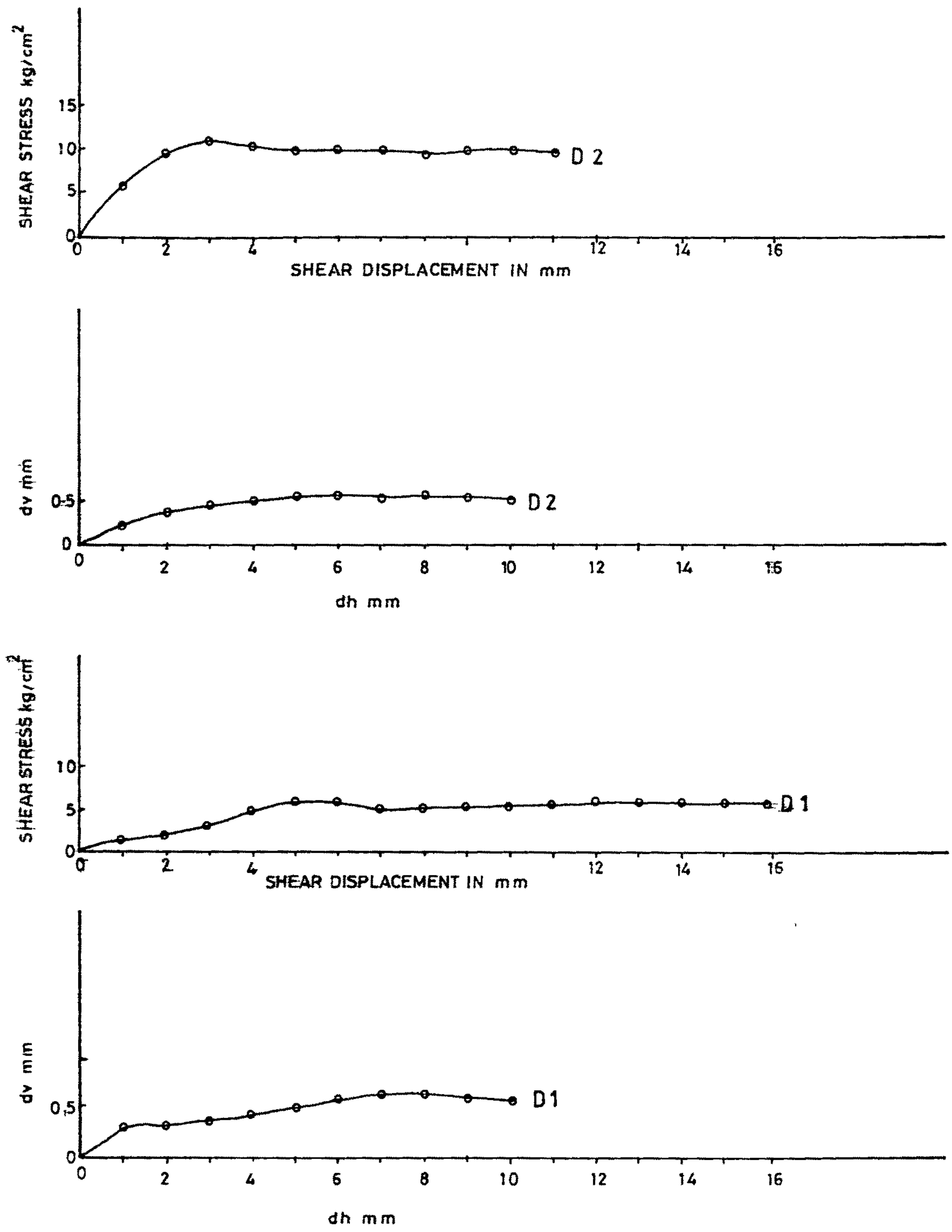


FIG: 6·25 (c) SHEAR STRESS-SHEAR DISPLACEMENT- NORMAL DISPLACEMENT RELATIONSHIPS

(DAVE 1987)

NOTATION	Description	C	Ø
•	ROCK TO ROCK	0	37
O	C:S=1:2	0	30
□	C:S=1:3	0	28
Δ	C:S=1:4	-0	26

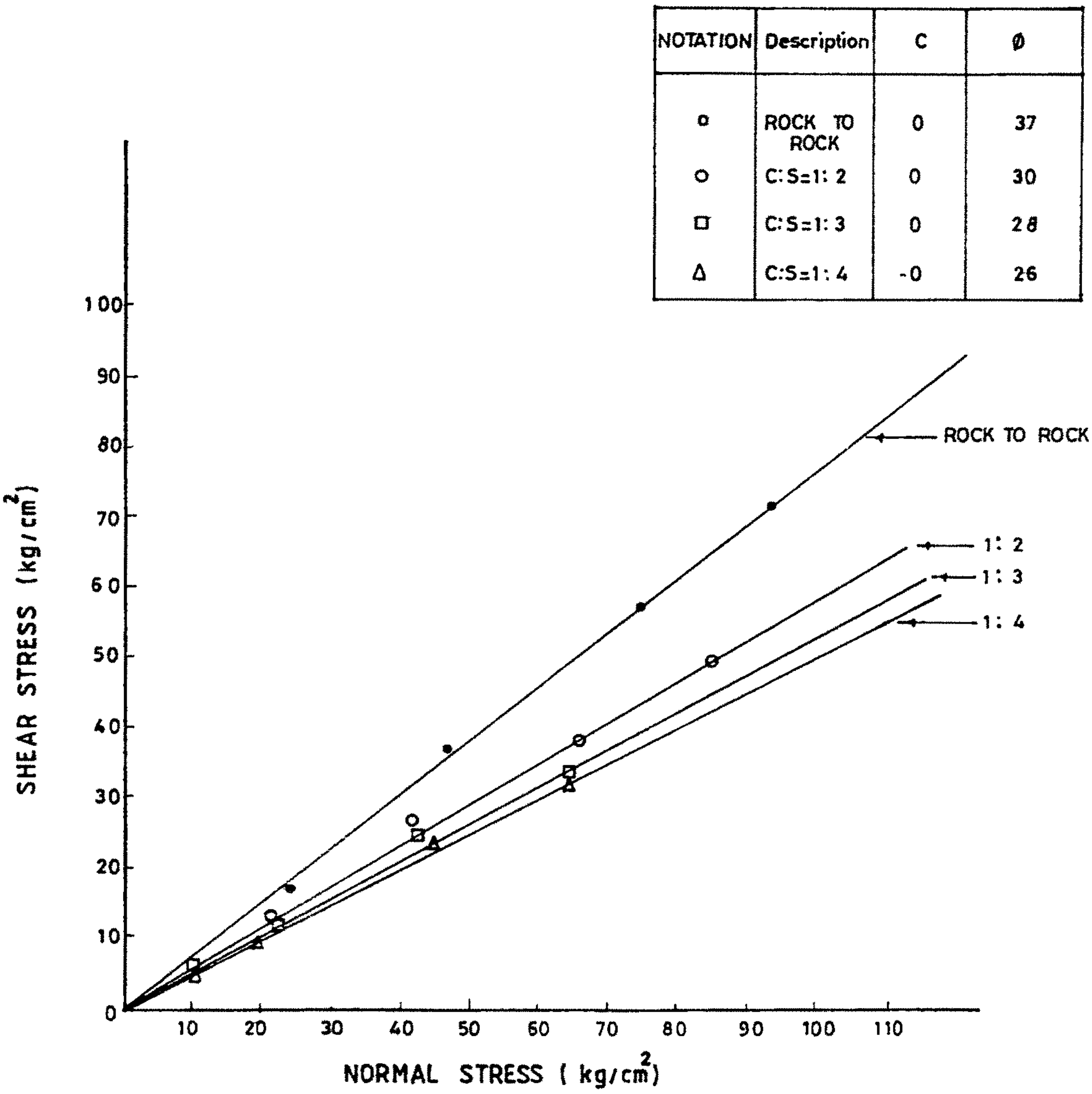


FIG: 6.26 SHEAR STRESS-NORMAL STRESS CHARACTERISTICS OF ALL SAMPLES

– DAVE (1987)

Some selective data from these tests are reproduced and presented as under :

Some typical plots of shear stress (σxy) versus shear displacements (du) and between vertical displacements (dv) with reprect to shear displacement (du), are reproduced in Fig. 6.27(a) to (c). Coulomb plots are presented in Fig. 6.28.

6.6 IN SITU DIRECT SHEAR EXPERIMENTS

6.6.1 In situ direct shear tests on concrete-rock interface were conducted and reported by Datir (1981). Some typical data from these tests are presented in Fig. 6.29 to 6.31. This data is subsequently utilised in verification of constitutive law developed during this investigation.

6.7 OBSERVATIONS FROM THE EXPERIMENTAL INVESTIGATIONS

6.7.1 Direct Observations

Following observations are made from the experimental investigations conducted for concept verification.

(i) Basic friction angle ϕ_μ of the plane surfaces is 42°.

(ii) No volume change - or dilation - occurs during sliding on plane surfaces.

(iii) Lubrication reduces the frictional resistance.

(iv) Regularly aspirated samples exhibit a friction angle equivalent to (ϕ_μ + i).

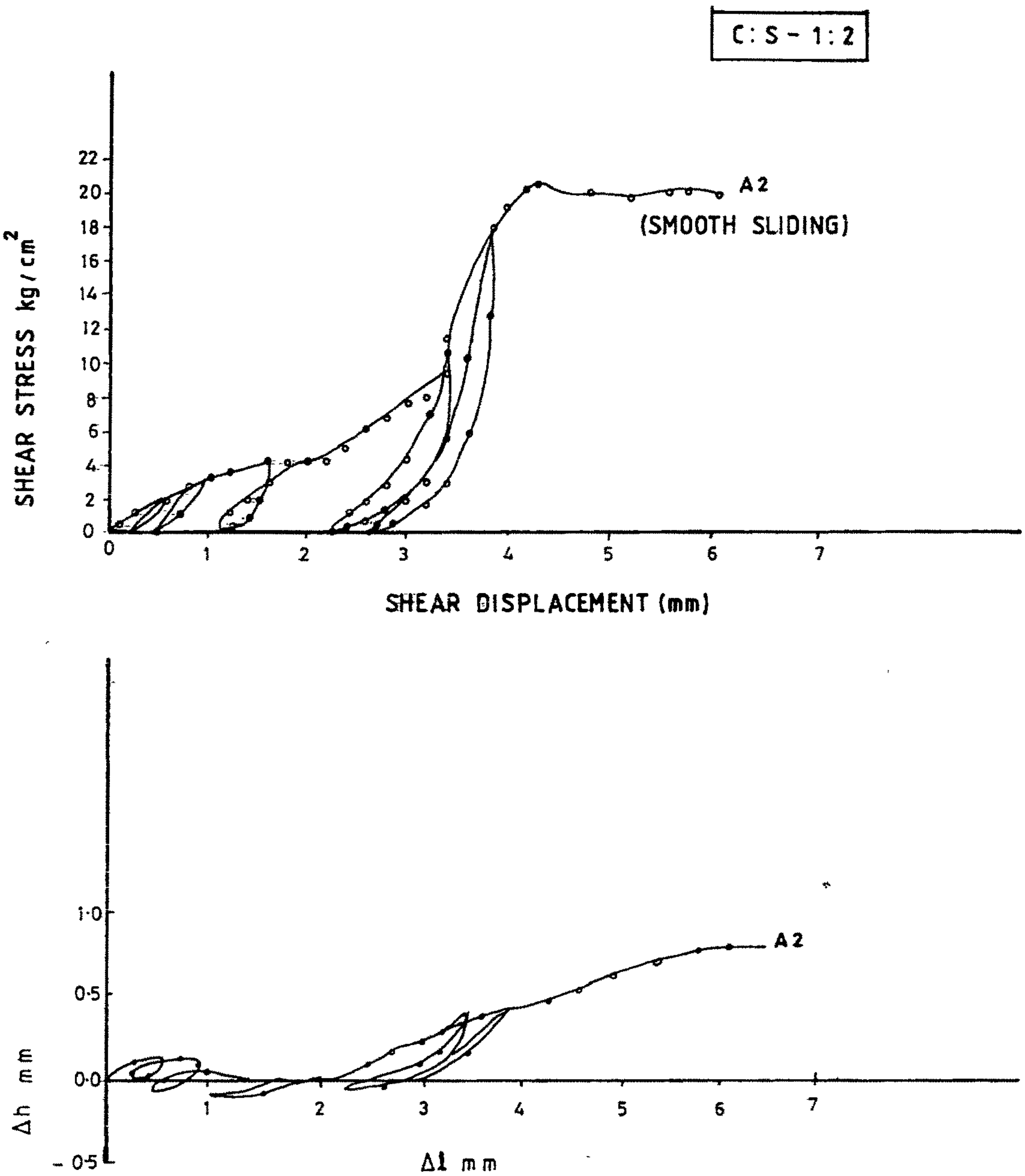


FIG: 6·27 (a) SHEAR STRESS - SHEAR DISPLACEMENT NORMAL DISPLACEMENT RELATIONSHIPS

-SHAH (1987)

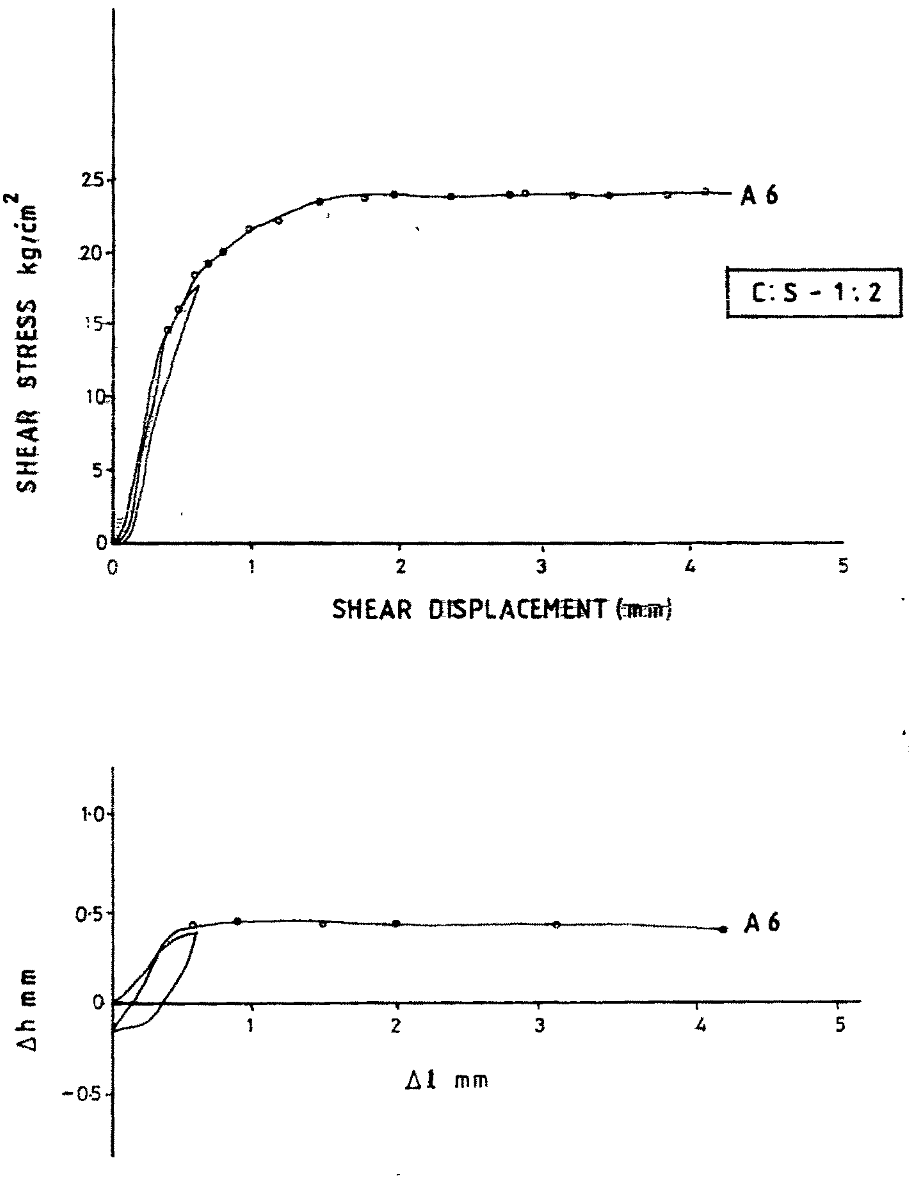
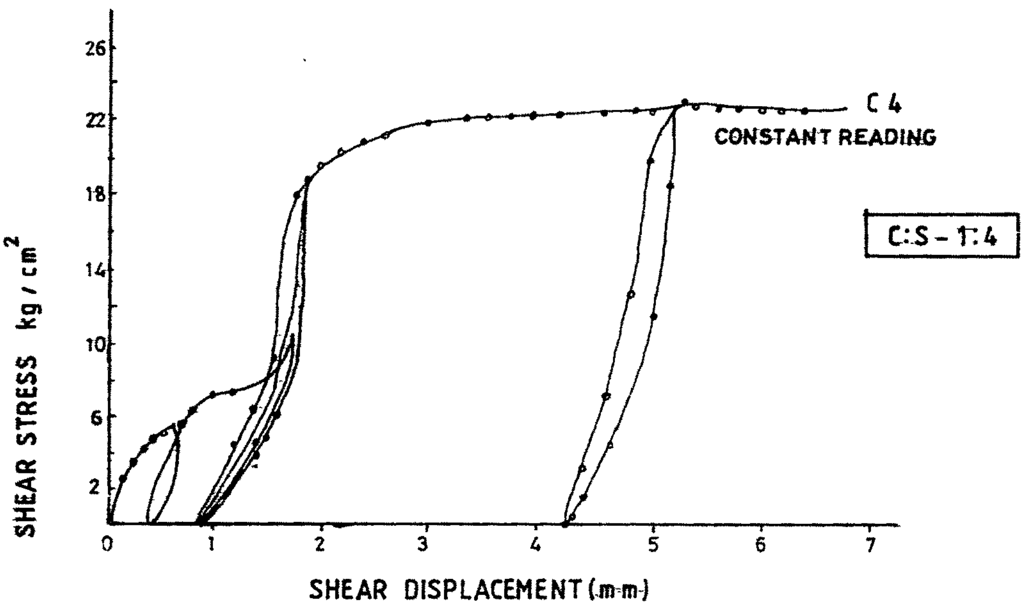


FIG: 6·27 (b) SHEAR STRESS - SHEAR DISPLACEMENT - NORMAL DISPLACEMENT RELATIONSHIP -SHAH (1981)



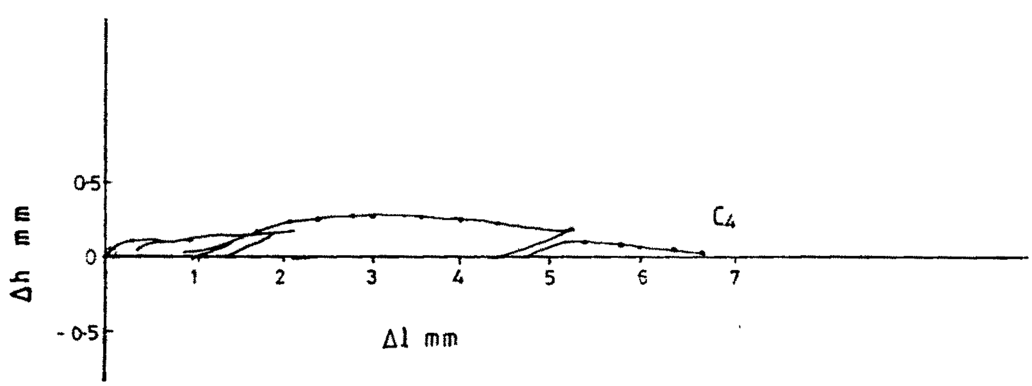


FIG: 6·27 (c) SHEAR STRESS - SHEAR DISPLACEMENT - NORMAL DISPLACEMENT RELATIONSHIPS -SHAH (1981)

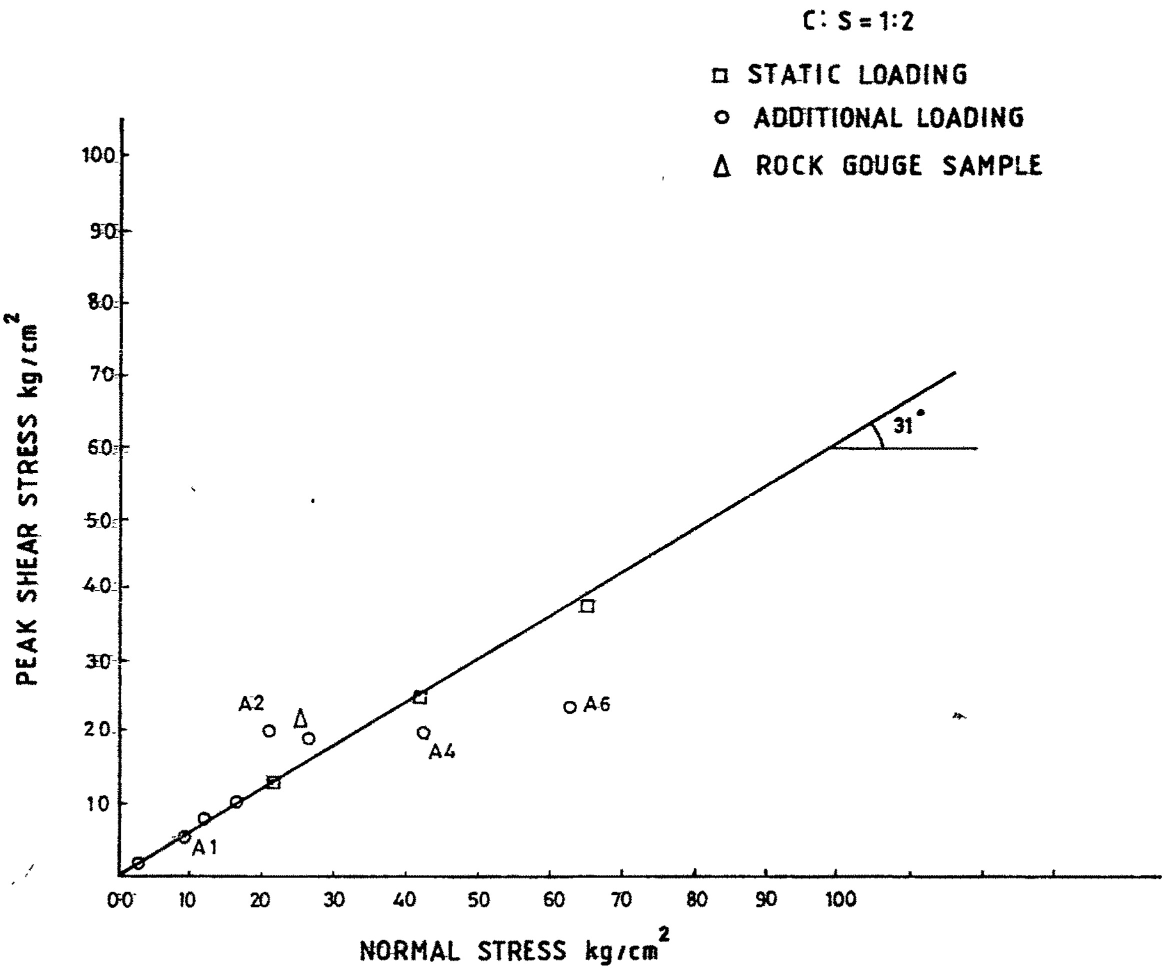


FIG: 6·28(a) SHEAR STRESS-NORMAL STRESS CHARACTERISTIC CURVE

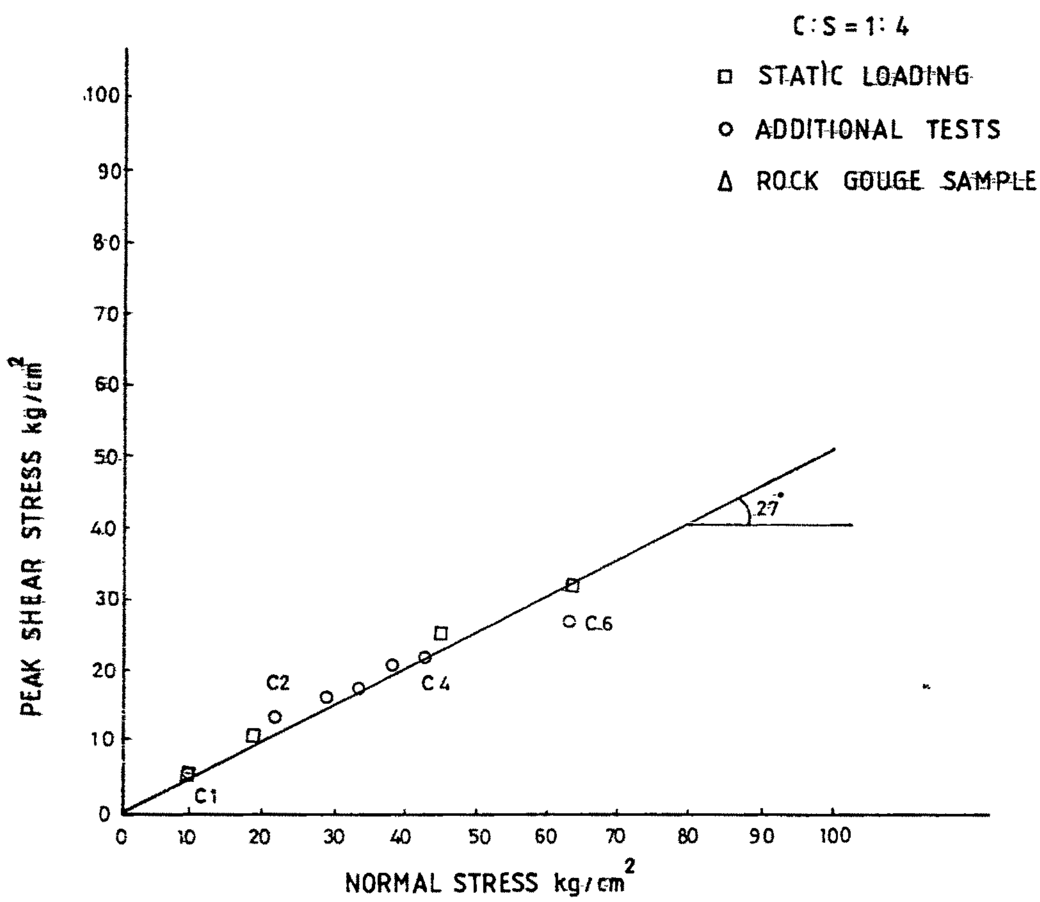


FIG: 6·28(b) SHEAR STRESS-NORMAL STRESS CHARACTERISTIC CURVE

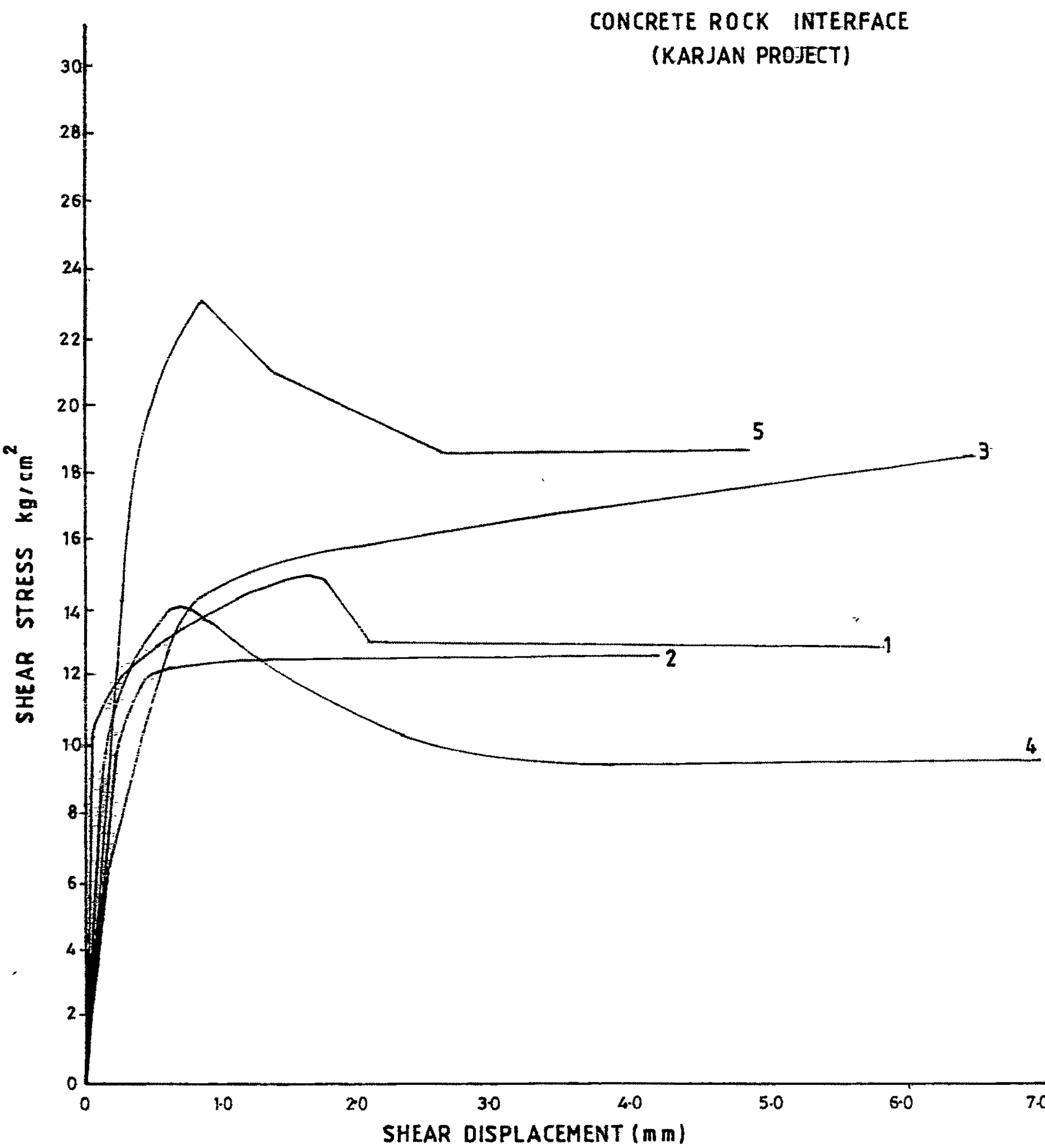


FIG: 6·29 PLOT OF SHEAR STRESS VERSUS SHEAR DISPLACEMENT

DATIR (1981)

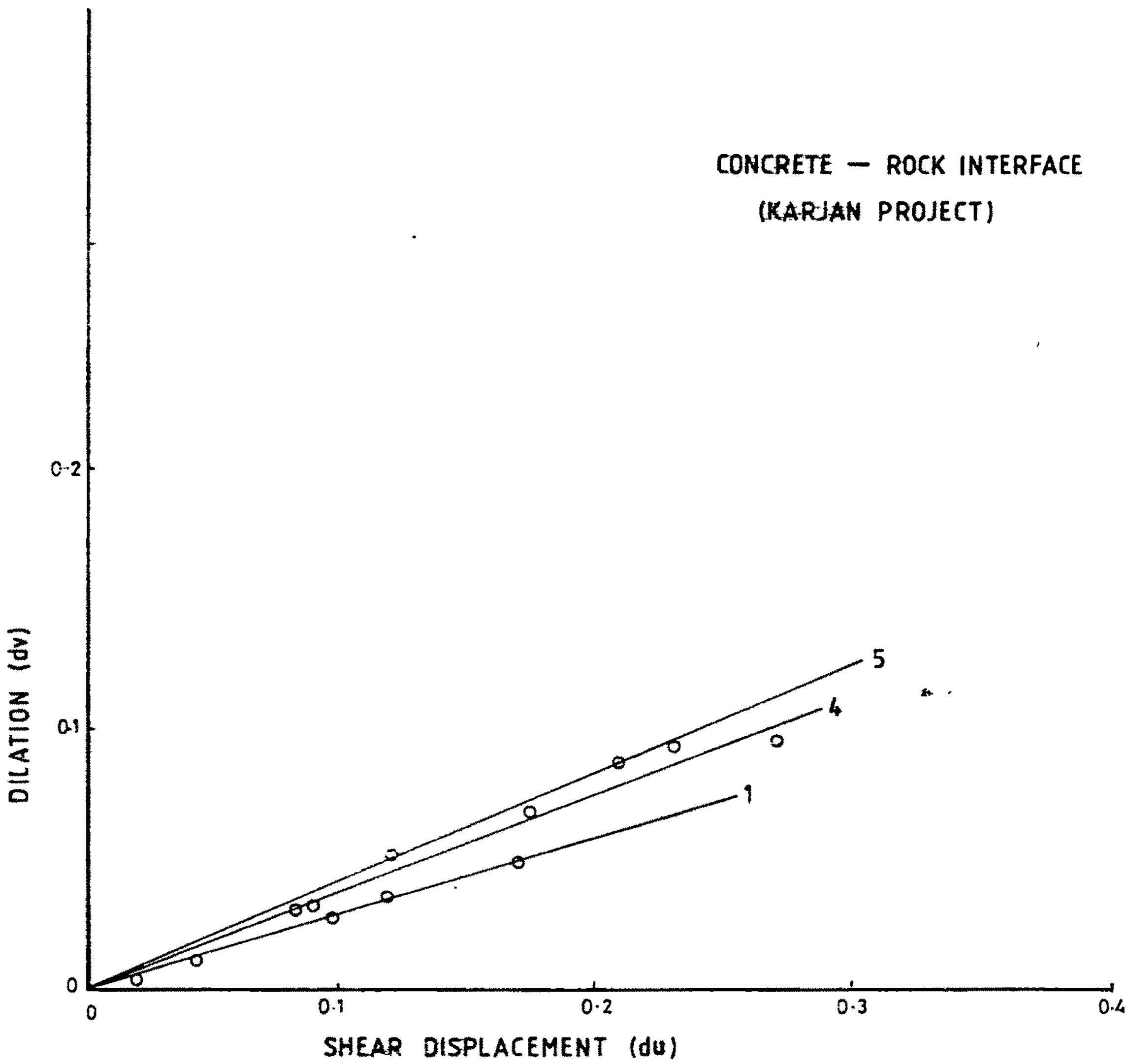


FIG: 6·30 PLOT OF DILATION (dv) VERSUS SHEAR DISPLACEMENT (du)

- DATIR (1981)

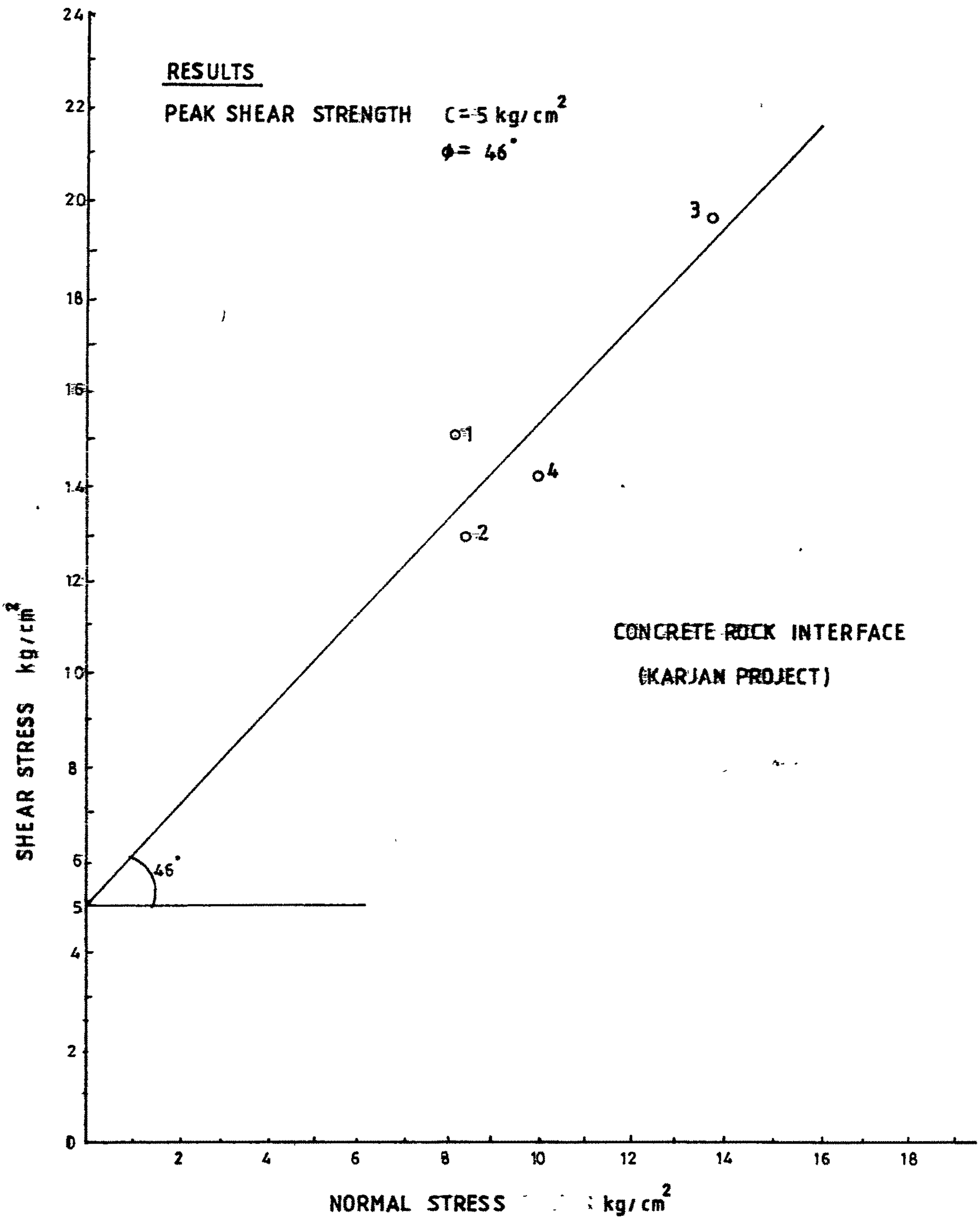


FIG: 6.31 PLOT OF SHEAR STRESS VERSUS NORMAL STRESS

-DATIR (1981)

(v) Irregularly aspirated plane surfaces exhibit an increase in the frictional resistance beyond basic friction.

(vi) Gouge in the form of cohesive material reduces the friction angle.

6.7.2 Critical Appraisal of Direct Observations compared with Others

(i) It is observed that coefficient of friction of plane surfaces is lower than that for roughened (irregularly aspirated) surfaces which are 0.90 and 1.33 respectively. This observation is in agreement with most of the research workers like Tschebotariof and Welch (1948), Riplex and Lee (1961), Byerlee (1967), Hoskins (1968), Coulson (1970).

(ii) It is observed that lubrication of plane surfaces reduces the frictional resistance. This observation confirms observation of Parikh (1967) and Proctor (1974) that value of Ø of a material is not only a function of the composition of the material of the surfaces but also of the surface chemistry.

(iii) It is observed that frictional resistance of unlubricated plane surface is 0.90, that of lubricated plane surface (with a thin layer of silicon grease) is 0.42 and it reduces to 0.32 when thickness of the lubricant is increased. Thus it is observed that even when the filler thickness is small there is a decrease in peak shear strength. This observation is in conformity with that of Lama (1978). It is further observed that when the thickness of filling material is increased the strength reduces gradually. This observation confirms the similar observation made by many investigators like Coulson (1970), Goodman (1970), Jeager (1969), Romero (1968), Tutinov et al (1971).

(iv) It is observed that peak shear strength envelope of regularly aspirated surfaces is curved. This is in agreement with observations made by Barton (1977) and Venkatachalam (1985).

(v) It is observed that a thin sand layer as a filler between the sliding surfaces (irregularly aspirated surfaces) of plaster of paris (model material) increases the angle of friction. This observation is in agreement with that of Tulinov and Molokov (1971) who observed that thin sand layer as a filler between surfaces of relatively weak material increases the angle of friction.

6.8 CONCLUDING REMARKS

The basic concepts regarding frictional resistance on sliding surfaces are verified in the present experimental investigation. It is verified that plane surfaces do not exhibit any volume change or dilation during sliding. It is also verified that frictional resistance of aspirated surfaces is nearly equivalent to tan ($\emptyset_\mu + i$). It is confirmed that lubrication reduces the frictional resistance. It is also confirmed that particles of fine sand (quartz) increases the frictional resistance whereas gouge in the form of soft material reduces the frictional resistance.