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BEHAVIOR OF LUBRICATION LAYERS OF PLATENS IN ELEMENT TESTS

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ABSTRACT

The results of a series of direct shear tests on lubrication layers and other related tests performed to get a better insight into the methods of lubrication between the sand samples and the platens are described. The lubrication layers used consist of grease and latex disc. To get a good quality of lubrication, it is first needed that the grease has an enough resistance against squeezing out when compressed. The inclusion of fine solid fillers in the grease increases this resistance, while as a result lubrication when not squeezed out becomes less effective with the increase in the amount of fillers as well. The quality of lubrication depends on the following factors at least; (1) the quality of grease (the viscosity of the base silicone oil and the amount of fine solid fillers included in the grease), (2) the normal stress, (3) the composition concerning latex disc and silicone grease. For the lubrication at low normal stresses, the following composition may be recommended; (1) the grease should be composed of low viscosity silicone oil and an appropriate amount of fillers, and (2) a smooth surface should be facing the grease layer. For the lubrication at high normal stresses the following composition may be recommended; (1) the grease should be composed of high viscosity silicone oil and an appropriate amount of fine fillers, and (2) a composition with which stress concentrations in the grease layer are reduced. By using an appropriate method of lubrication the apparent angle of friction for a lubrication layer placed between a fine angular sand mass and a steel platen can be much smaller than 1 degree for normal stresses of 150～670 kN/m^2 at least.

Key words: laboratory test, sandy soil, shear strength, stress distribution, test procedure, triaxial compression test (**IGC**: D 0/D 6)

INTRODUCTION

For samples loaded by platens, as in the common triaxial tests, the measured strengths and the non-uniformities of stresses and deformations will depend on the quality of the lubrication between the samples and the platens. For the lubrication in the simple

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shear tests Roscoe (1953) inserted a rubber membrane with a thickness of about 50 μm and a silicone DC 7 grease layer between the plasticine samples and the brass side plates. Rowe and Barden (1964) introduced lubrication in triaxial tests by putting a thin layer of silicone grease and a circular rubber membrane on the polished aluminium alloy end platens. They found that the shear stress on the lubrication layer increased slightly with both the speed of shearing and the normal stress. The effective "angle of friction" was reported to be less than 1 degree for normal stresses larger than about 70 kN/m^2. Arthur and Dalili (1979) used another kind of grease for the lubrication between the rubber surfaces in their directional shear cell. The optimum lubrication with 4 degree of effective "angle of friction" for normal stresses between 50 kN/m^2 and 400 kN/m^2 was obtained with 50 percent in weight of PTFE (Polytetra Fluoroethylene) powder added to Molykote 111 compound.

To get a better insight into the quality of present lubrication methods of the end platens also for low normal stresses and alternating loading a series of squeezing-out tests and a series of direct shear tests were performed. Also a series of triaxial compression tests on samples with lubricated ends having different height to diameter ratios was performed to show the effect of the quality of lubrication on the measured strengths of the samples. In this testing program Toyoura sand with a mean grain size of 0.16 mm and an angular shape has been used. All latex membranes had a thickness of about 300 μm.

TEST PROGRAM

The following kinds of tests were performed:

1. Compression tests on thin layers consisting of either grease or silicone oil or a mixture of PTFE-powder and grease placed between two parallel smooth circular platens. The purpose of the tests was to determine the speed by which such layers are squeezed out due to the application of pressure. This kind of information is needed to identify the properties (viscosity) of the lubricant.
2. Direct shear tests on lubrication layers placed between a sand mass and a smooth platen under controlled pressure to evaluate directly the quality of lubrication of such layers. Several different compositions concerning latex discs and silicone grease were tested.
3. Direct shear tests on lubrication layers placed between two parallel platens. The different lubrication layers consisted of a latex disc and a grease or a grease-powder mixture. The purpose of this test was to evaluate the effect of powder inclusions in grease on the shear resistance of the lubrication layers.
4. Triaxial compression tests on samples with lubricated ends under a relatively low confining pressure (98 kN/m^2) to evaluate the quality of lubrication directly as performed by Bishop and Green (1965). The height to diameter ratios employed were 15 to 7, 7 to 7, 4 to 7 and 2 to 7.

COMPRESSION TESTS

Test Materials: Two kinds of silicone grease and one kind of silicone oil (see Table 1) were selected. Silicone oil compound KS 63 G, provided by Shin-etsu Chemical Company Ltd. (this will be called Silicone grease KS 63 G in the following), is composed of thin base silicone oil and fine angular silica fillers. The base silicone oil is Shin-etsu silicone oil KF 96 which has a nominal viscosity of around 500∼1 000 Poise (g/cm/s). The precise compositions of Silicone grease KS 63 G are not opened by the company. The mean diameter of silica fillers was estimated around 7 μm from a magnified photograph of a thin layer of this silicone grease. Using the same photograph the mass ratio of the silica-filler with respect to the total weight of the grease was estimated as around 2%.

Dow high vacuum silicone grease (this will be called Dow grease in the following)

Table 1. Greases and oil used in this study

Name	Type	Colour	Contents	Specific Density
Silicone Oil Compound, KS 63 G*	Grease (Oil Compound)	Green	Silicone Oil and Silica Filler	1.06
High-Vacuum Grease**	Grease (Oil Compouud)	Light Gray, Translucent	Silicone Oil and Fine Filler	1.1
Silicone Oil KF 96-1 000 000*	Oil	Colorless and Transparent		0.975

* Provided by Shin-etsu Chemical Company Limited.
** Provided by Dow Corning Corp.

is presently used for lubrication of platens in many soil laboratories. It was found from a magnified photograph of a thin layer of Dow grease that Dow grease includes rectangular-shaped silica fillers which have dimensions of around 28 μm × 50 μm × 50 μm. The mass ratio of fillers was estimated as 0.1% which is a much smaller number than that of Silicone grease KS 63 G. The base silicone oil is much thicker (more viscous) than that of Silicone grease KS 63 G.

Shin-etsu silicone oil KF 96-1 000 000 (this will be called Silicone oil KF 96 in the following) was selected to determine the difference in properties between silicone grease and silicone oil when squeezed out from the space between the flat smooth platens. The nominal viscosity of this oil is reported as 10 000 Poise at a temparature of 25 degree C. This value is around 10 to 20 times larger than that of the base silicone oil of Silicone grease KS 63 G. Note that oil does not include fine fillers.

To obtain some insights into the role of the fine fillers included in silicone grease in the generation of the resistance against squeezing out, two compression tests were performed on the thin layers of the mixture of either Silicone grease KS 63 G or Dow grease and PTFE powder. The weight ratio of powder to grease was 3 to 2. The mean diameter of PTFE powder ranged from 5 to 10 μm. The shape of these powder particles was angular. The grease-powder mixtures were prepared by mixing thoroughly during 10 to 15 minutes using a spatula and a glass plate.

Test setup: The general setup of the compression tests is shown in Fig. 1 which is similar to that employed by Molenkamp and

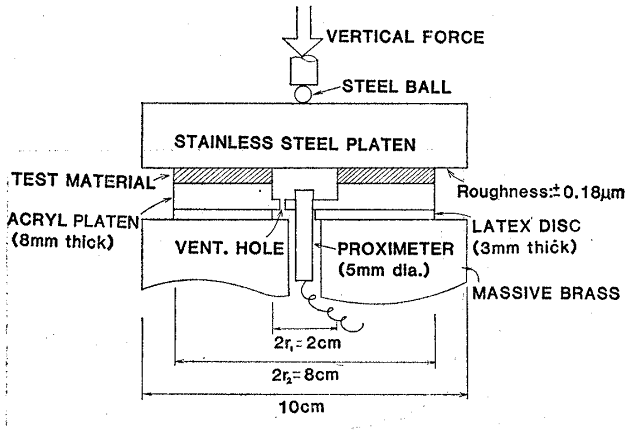

Fig. 1. Schematic diagram showing setup of compression test (not scaled)

Weenen (1981). In the present tests a highly sensitive proximeter (Model ASC-2525-05, Denshi-Oyo Corp.) was placed at the center of platen to measure the thickness of test material directly and continuously. The specification of this proximeter is as follows: sensitivity: 150 μm per volt, measuring range: 1.5 mm, resolution: infinite, and linearity: 1% of full scale. The proximeter was fixed to an acryl platen which has an inner hollow with a diameter of 2.0 cm. A very small ventilation hole was made inside this inner hollow. This inner hollow was introduced to simulate the geometry of the lubrication layer for triaxial tests in which a small drainhole is placed at the center of the end platens. In this compression test the grease or oil is squeezed out under pressure towards both the periphery and the center of the platens like in the preparation process of the lubricated ends for triaxial tests. To prepare a uniform thin layer of grease or oil on the acryl platen, a device shown in Fig. 2 was used following the method suggested by Molenkamp and

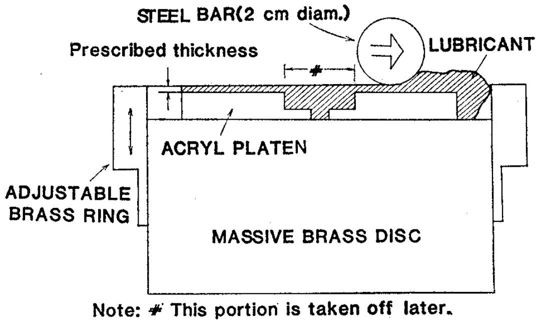

Fig. 2. Schematic diagram showing device to make uniform thin layer of test material (not scaled)

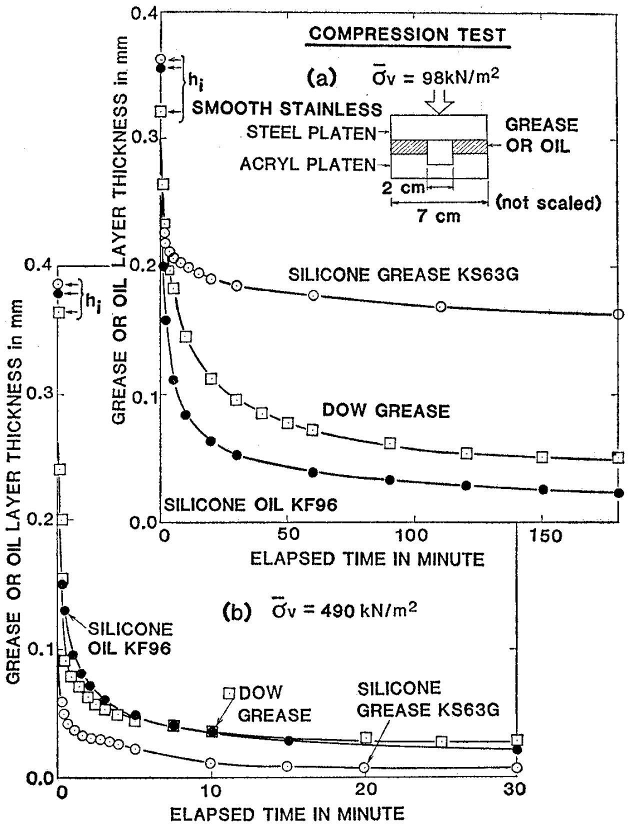

Fig. 3. Results of compression tests on greases and oil

Weenen (1981).

Test results: Results of compression tests on thin layers of grease or oil under mean vertical stresses $\bar{\sigma}_v$ of 98 kN/m² and 490 kN/m² are shown in Fig. 3(a) and Fig. 3(b) respectively. In these figures h_i means the initial average thickness of the grease or oil layer measured before the application of the vertical stress. The vertical stress was applied instantaneously. From Figs. 3 (a) and (b) the following points may be seen:

(1) Under a mean vertical pressure $\bar{\sigma}_v$ of 98 kN/m² the speed of squeezing out is the largest for Silicone oil KF 96, intermediate for Dow grease and the smallest for Silicone grease KS 63 G. In particular, the major part of Silicone oil KF 96 was squeezed out within around 20 minutes. On the other hand, the major part of Silicone grease KS 63 G remained in place even after a long elasped time. In another test (only in this test, the diameter of inner hollow was 1.0 cm), the thickness of the layer of Silicone grease KS63G with a h_i of 0.193 mm decreased even after 3800 minutes (around 2.6 days) only to 0.119 mm under $\bar{\sigma}_v=98$ kN/m².

(2) The change in the speed of squeezing out with the increase in $\bar{\sigma}_v$ from 98 kN/m² to 490 kN/m² is the largest for Silicone grease KS 63 G, intermediate for Dow grease and the smallest for Silicone oil KF 96. In particular, most of the Silicone grease KS 63 G was squeezed out in one minute under $\bar{\sigma}_v=490$ kN/m² while for Dow grease this took about 10 minutes.

(3) The two types of grease tested were not squeezed out completely even under $\bar{\sigma}_v=490$ kN/m². It was clearly observed after the compression test that at least for Silicone grease KS 63 G one layer of filler of the greases was left (see Fig. 3(b)).

An additional test was performed under $\bar{\sigma}_v=98$ kN/m² in which a latex disc with a thickness of around 300 μm was inserted between the grease layer and the top steel platen. The result of this test was very similar to the results of the tests in which this latex disc was not inserted. This may indicate that the performances shown in Fig. 3 can also be expected in the lubrication layer in triaxial tests during the preparation phase in which grease or oil layers are placed between a latex disc and an end platen.

Shown in Fig. 4 are the results of compression tests on the mixtures of PTFE powder and grease placed between two parallel smooth platens. The mean vertical stresses were 490 kN/m² and 980 kN/m². Note that

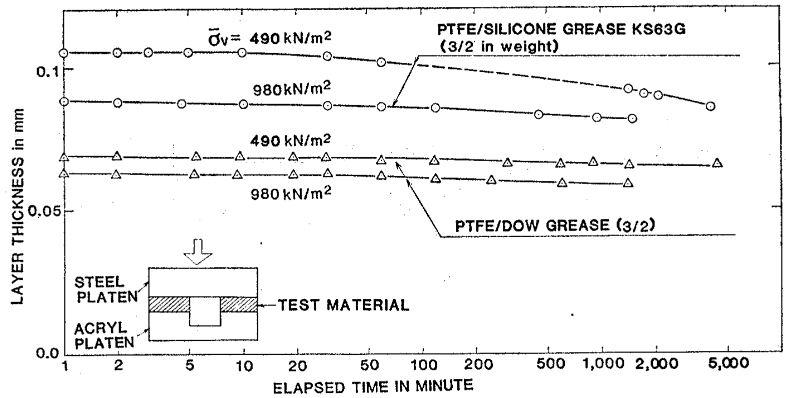

Fig. 4. Test results on powder-grease mixtures

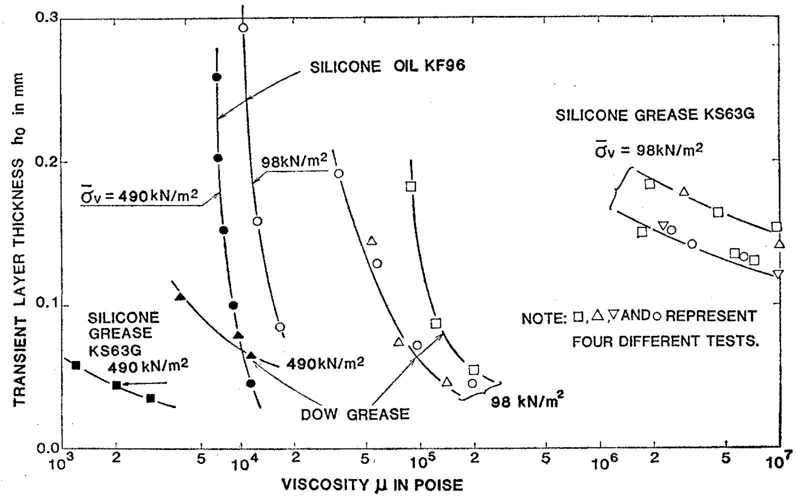

Fig. 5. Viscosity values estimated for greases and oil

the scale for elapsed time in Fig. 4 is logarithmic. It may be seen that the resistance against squeezing out was increased remarkably by adding PTFE powder to grease. These results may suggest that squeezing out of the lubricant from the space between the latex discs and the end platens in triaxial tests with long duration and/or under high pressure may be reduced by using a lubricant with a higher powder content.

Analyses: Molenkamp and Weenen (1980) have derived a theoretical solution of squeezing out of a thin layer of grease or oil placed between two parallel platens assuming that the material is a perfectly Newtonian viscous material. The viscosity value μ is obtained as:

$$\mu=\frac{2}{3\alpha}\left\{\frac{\ln(r_2/r_1)}{(r_1^2+r_2^2)\ln(r_2/r_1)-r_2^2+r_1^2}\right\} \quad (1)$$

in which r_1=inner radius, and r_2=outer radius (see Fig. 1). The quantity of the parameter α can be determined from the relation:

$$(h_0/h)^2=2\alpha\bar{\sigma}_v h_0^2 t+1 \quad (2)$$

in which h=transient thickness of the grease layer, h_0=initial thickness, $\bar{\sigma}_v$=mean normal stress on lubrication layer, and t= elapsed time from an arbitrary initial time at which h_0 is defined. It was found that relationship between $(h_0/h)^2$ and t obtained from the data shown in Fig.3 were not linear. This may be because the test materials were not perfectly Newtonian viscous materials. Therefore, in each test several elapsed times were selected as t_0 and also the corresponding transient thicknesses h were defined h_0 for $t=t_0$. The quantities α and μ were determined as a function of transient initial thickness h_0 (Fig. 5). In Fig. 5 also other data than shown in Fig. 3 are included. It may be seen that the viscosity value thus obtained decreases with the increase in $\bar{\sigma}_v$ in the largest degree for Silicone grease KS 63 G, in the intermediate degree for Dow grease and in the smallest degree for Silicone oil KF 96. This may indicate that the viscosity of silicone grease becomes more sensitive to pressure when the amount of fillers is increased.

In summary, the inclusion of fillers or powders in silicone grease increases the resistance against squeezing out under pressure. However when the amount of fillers is smaller than or equal to that of Silicone grease KS 63 G the resistance against squeezing out decreases rapidly with the increase in pressure. Even thick silicone oil as Silicone oil KF 96 will be squeezed out under a low normal stress after a sufficient long time. This kind of oil can not be recommended as a lubricant for end lubrication in soil testing, especially for that in tests of long duration.

DIRECT SHEAR TESTS ON LUBRICATION LAYERS BETWEEN SAND MASS AND PLATEN

Test materials: Silicone grease KS 63 G and Dow grease were selected as the test materials which can be considered suitable for usage in laboratory tests. Silicone oil KF 96 was not used because it had become clear that this oil could not be used as lubricant due to its low resistance against squeezing out under pressure.

Test setup: Cyclic displacement-controlled direct shear tests were performed at controlled vertical load by using an apparatus schematically shown in Figs. 6 and 7. Angular fine silica sand (Toyoura sand, mean diameter $d_{50}=0.16$ mm, uniformity coefficient$=1.46$ and specific gravity$=2.64$) with a void ratio of around 0.73 was placed into the acryl ring by the air pluviation method. The inside wall surface of the acryl ring was lubricated with a layer of Silicone grease KS 63 G with a thickness of around 100 μm and a 300 μm thick latex membrane.

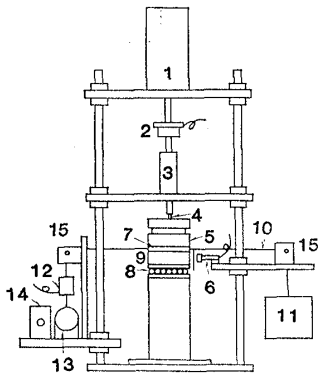

Fig. 6. Schematical diagram showing direct shear apparatus

1. Bellofram cylinder to control vertical load
2. Load cell to measure vertical load
3. Bearing house to guide loading piston
4. Steel ball
5. Sand mass or steel platen
6. Proximeter to measure horizontal displacement of 7
7. Polished stainless steel platen (surface roughness ; ± 0.035 μm, 8 mm thick)
8. Bearing
9. Massive brass disc
10. Steel wire
11. Dead weight (5 kg or 10 kg)
12. Load cell (capacity ; 200 N)
13. Reversible moter
14. Speed and direction control panel for 13
15. Pulleys

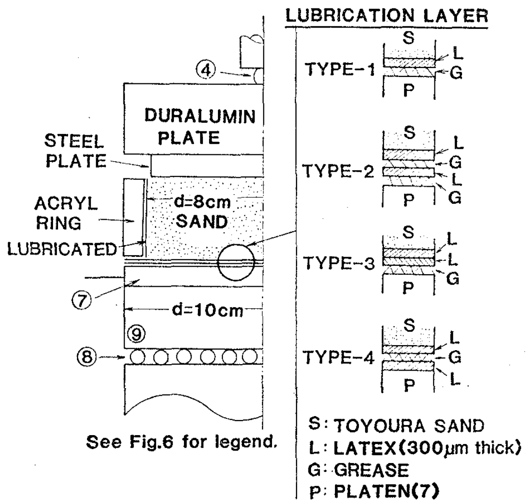

Fig. 7. Detailed picture showing compositions of lubrication layers tested

Four kinds of compositions of lubrication layers were tested (see Fig. 7), namely: Type 1 ; One layer of grease is placed between a latex disc (300 μm thick) and a polished stainless steel platen. Type 2 ; The

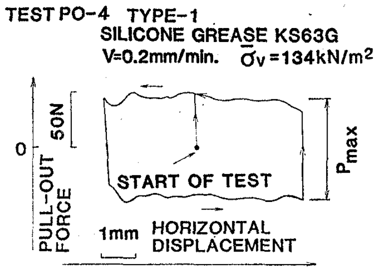

Fig. 8. Typical measured load-displacement relationship

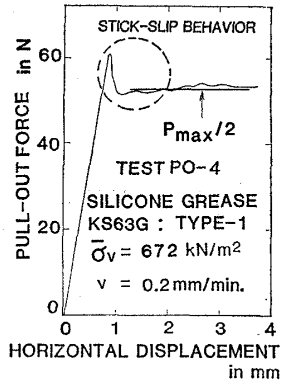

Fig. 9. Typical measured stick slip behaviour

lubrication layer of type 1 is doubled. Type 3; One layer of grease is placed between two latex discs (600 μm thick in total) and a polished stainless steel platen. Type 4; One layer of grease is placed between two latex discs. This set is put on a stainless steel platen.

The initial thickness of the grease layers was around 50 μm. Averaged thickness values of grease layers before and after tests will be indicated in the figures concerned. One cycle of direct shear with a double amplitude horizontal displacement of 4 mm to 6 mm was applied under a constant vertical stress (see Fig. 8). The vertical stress was then increased to another value and a similar cyclic test was repeated. In Fig. 8 is shown a typical result, which was obtained in the sequence where $\bar{\sigma}_v$ was increased between different direct shear tests. In most tests several values of the mean vertical stress $\bar{\sigma}_v$ were applied ranging between 5.5 kN/m^2 and 692 kN/m^2. In most tests the direct cyclic shear tests were continued also after application of the maximum $\bar{\sigma}_v$ with decreasing $\bar{\sigma}_v$ (see Figs. 11 through 13). After the application of each new mean vertical stress $\bar{\sigma}_v$ a consolidation time was allowed before the application of the cycle of direct shear. These consolidation times were 10 minutes for $\bar{\sigma}_v$=5.5 kN/m^2, 30 minutes for $\bar{\sigma}_v$=26.9 kN/m^2 and 60 minutes for $\bar{\sigma}_v$=98 kN/m^2 or larger. The horizontal displacement rate v was 0.2 mm/min in most tests. In some tests, this rate was varied between 0.1 and 0.5 mm/min or between 10 and 50 mm/min to determine the effect of displacement rate on the shear resistance of the lubrication layer.

Test results: A typical recorded relationship between pull-out force and horizontal displacement is shown in Fig. 8. The pull-out force was measured with a load cell (12 in Fig. 6) and the horizontal displacement was measured with a proximeter (6 in Fig. 6). The mean shear resistance of the lubrication layer was estimated as:

$$\bar{\tau}_{max} = (P_{max}/2 - F)/A \qquad (3)$$

in which P_{max} is the double amplitude pull-out force (see Fig. 8), F is the single amplitude total frictional force in the bearing (8 in Fig. 6) and in the pulleys (15 in Fig. 6) and A is the cross-sectional area of sand sample (57.3 cm^2). The value of F was carefully calibrated as a function of $\bar{\sigma}_v$ and the dead weight (11 in Fig. 6). The value of F ranged from 0.5 N to 2.6 N. Stick slip behaviours as indicated in Fig. 9 were observed only in some tests for Silicone grease KS 63 G tested at $\bar{\sigma}_v$=672 kN/m^2. When such a stick slip behaviour was observed, the value of P_{max} was defined as the residual pull-out force (Fig. 9). Although the shear resistance of the lubrication layers is not completely of the frictional type as shown later, the apparent frictional angle was defined as:

$$\varphi = \arctan(\bar{\tau}_{max}/\bar{\sigma}_v) \qquad (4)$$

In Fig. 10 the effects of the displacement rate on the value of φ are shown for Silicone grease KS 63 G. The displacement rate could be changed by a factor 5 by adjusting the input voltage to the motor (13 in Fig. 6). To obtain larger changes in the displacement

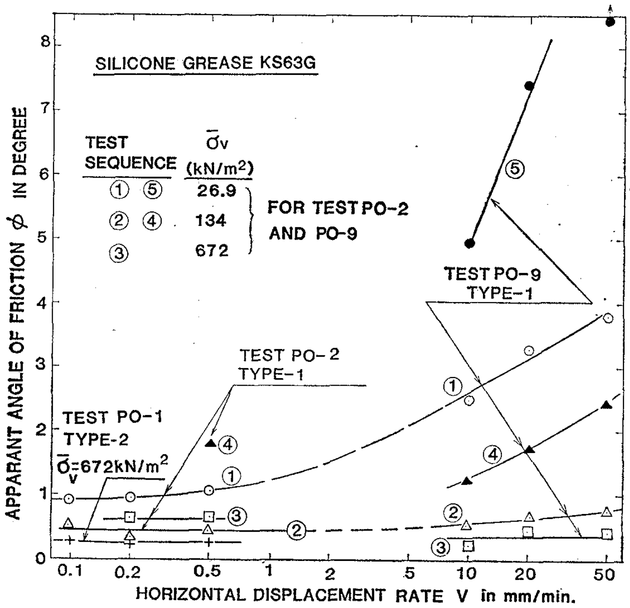

Fig. 10. eflects of shearing speed on φ

rate the number of gear boxes had to be changed. Becuase such change of the gear boxes would probably lead to a disturbance of the test material, two different test samples (tests PO-2 for low displacement rates and PO-9 for high displacement rates) were prepared to obtain a wider variation in v up to a factor of 500. Also in Fig. 10 are shown the results of another test at a low displacement rate (test PO-1). It may be seen that when the value of φ is less than around 1 degree it becomes quite independent of displacement rate. It may also be seen that the dependency of φ on the displacement rate increases with the increase in φ when φ becomes larger than 1 degree. All the other tests were performed at a displacement rate of 0.2 mm/min. Therefore the test results in the case where φ is less than 1 degree may also be valid for other displacement rates. If the material would be purely frictional, then the value of φ would be independent of the displacement rate. Therefore, the behaviour shown in Fig. 10 indicates frictional behaviour for small values of φ ($\varphi \leq 1$ degree). For higher apparent friction angles φ the behaviour seems to be at least partly viscous too.

The summarized relationships between φ and $\bar{\sigma}_v$ are shown in Figs. 11 through 14.

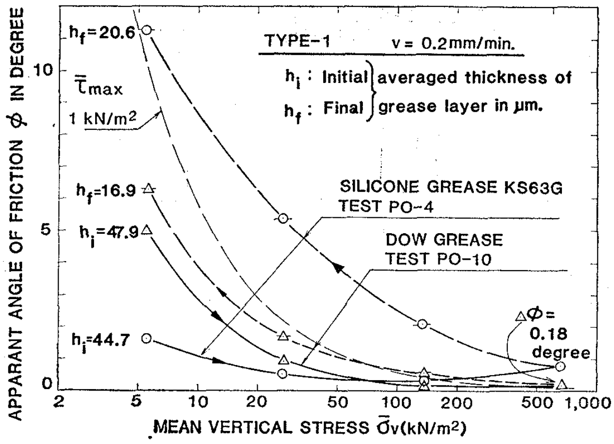

Fig. 11. Values of φ for lubrication layer of Type 1

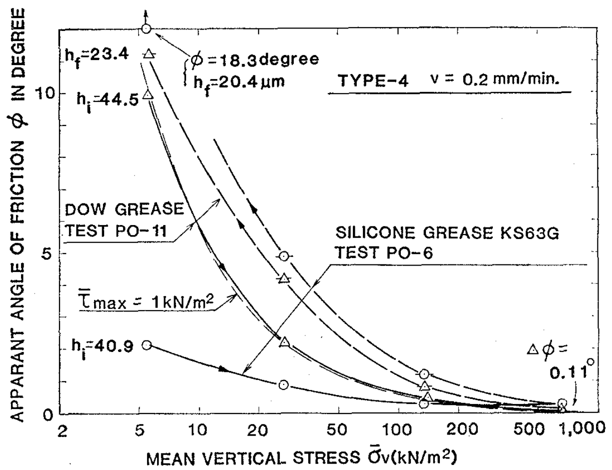

Fig. 12. Values of φ for lubrication layer of Type 4

The broken curves seen in these figures represent constant values of $\bar{\tau}_{max}$. The following points may be seen from these figures:

(1) In types 1 and 4, the quality of lubtication with Silicone grease KS 63 G is better than that with Dow grease for $\bar{\sigma}_v$ lower than around 150 kN/m² during increasing $\bar{\sigma}_v$. The low viscosity of base silicone oil used in Silicone grease KS 63 G may attribute to this performance. On the other hand the quality of the lubrication layer with Dow grease is better than that with Silicone grease KS 63 G for $\bar{\sigma}_v$ being larger than around 150 kN/m² and also in the whole range of $\bar{\sigma}_v$ during decreasing $\bar{\sigma}_v$. Supposing that the apparent friction angle increases with the increase in the number of direct contacts between the latex disc and the polished steel

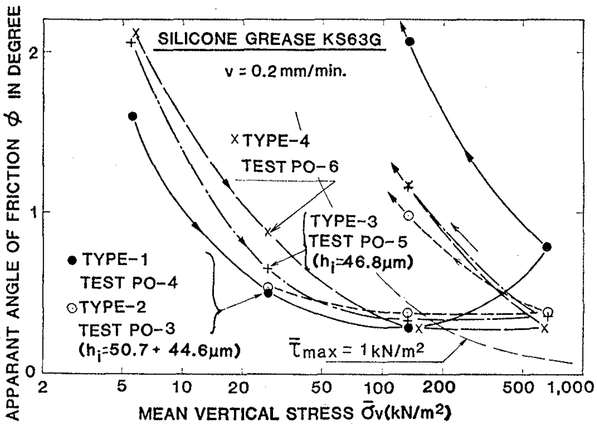

Fig. 13. Values of φ for silicone grease KS 63 G

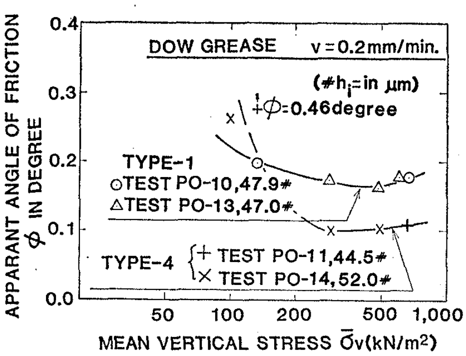

Fig. 14. Values of φ for Dow grease

platen in type 1 or between both latex discs in type 4, the present results suggest that for Silicone grease KS 63 G this number of direct contacts increases much faster with increasing $\bar{\sigma}_v$ than for Dow grease. This supposition is consistent with the measured friction during decreasing $\bar{\sigma}_v$ for which a relatively large increase in φ during decreasing $\bar{\sigma}_v$ was obtained for Silicone grease KS 63 G when compared with the increase for Dow grease. For both kinds of grease the apparent friction angles increased less fast with decreasing $\bar{\sigma}_v$ than according to the curves of constant maximum mean shear stress $\bar{\tau}_{max}$.

From the findings described above, Silicone grease KS 63 G can be recommended for end lubrication for monotonic loading at low normal stresses. Dow grease can be recommended for end lubrication for monotonic loading at high normal stresses. For alternating loading of the mean normal stress $\bar{\sigma}_v$ Dow grease shows less deterioration and therefore it can be considered more suitable for such stress paths. However for mean normal stresses $\bar{\sigma}_v$ less than about 50 kN/m^2 the apparent friction angle φ will be larger than 1 degree. Thus in fact for cyclic loading of the mean normal stress below this value both greases are unsatisfactory. If the final deterioration of the quality of lubrication due to many cycles of shearing would be similar to the deterioration due to cyclic normal stress $\bar{\sigma}_v$ like mentioned before then in the stress range above 50 kN/m^2 Dow grease would be a suitable lubricant while for the lower normal stress range both greases would be unsatisfactory. However the present experimental data are insufficient to arrive at any conclusion on the quality of lubrication for many cycles of shearing.

(2) For both kinds of greases the composition of type 1 showed a higher quality of lubrication than the composition of type 4 for $\bar{\sigma}_v$ less than around 150 kN/m^2. The difference between the two types is that a grease layer is placed directly on a polished stainless steel platen in type 1, while in type 4 a grease layer is placed on a latex disc which is put on a polished stainless steel platen. The surface roughness of the latex disc is much larger than that of the polished stainless steel platen. It is likely that the smooth surface facing the grease layer is important for good lubrication at low normal stresses. On the other hand it may be seen from Figs. 13 and 14 that the quality of lubrication of the composition of type 4 is better than the composition of type 1 when $\bar{\sigma}_v$ is larger than around 150 kN/m^2. In particular, it can be seen in Fig. 13 that for type 1 with Silicone grease KS 63 G the value of φ at $\bar{\sigma}_v$=672 kN/m^2 is more than twice as large as the value of φ at $\bar{\sigma}_v$=134 kN/m^2. If the friction would be mainly transmitted at the points where the grains indent the latex disc then from the present results it would follow that the stress concentrations in the grease layer near those grains would be less in type 4 than in type 1 due to the extra flexibility of another latex disc. Therefore, this result may be showing

that to increase the quality of lubrication under a high normal stress, the stress concentrations at contact points should be reduced by increasing the number of latex discs or by increasing the t/d_{50} ratio (t=latex disc thickness and d_{50}=mean diameter of sand). This point seems to be supported by the results shown in Fig. 13. In the lubrication layers of types 2, 3 and 4 two latex discs are used with different compositions. The qulities of these three types of compositions are very similar without showing an increase in φ with the increase in $\bar{\sigma}_v$ from 134 kN/m^2 to 672 kN/m^2 in spite of the fact that the roughnesses of the surface facing the grease layer differ significantly among these tests. Among these types of compositions type 4 may be recommended for higher normal stresses because of its lower Poisson's effect (Norris, 1980), resulting in lower bedding error; because the two latex discs are restrained by both the sand and the steel platen.

(3) The value of φ was reduced to around 0.1 degree for a range of $\bar{\sigma}_v$ from around 300 to 700 kN/m^2 when type 4 composition with Dow grease was used (Fig. 14). This value of φ is much less than the values of φ reported in the literature (Rowe and Barden, 1964; Bishop and Green, 1965; Lee, 1978).

In summary, it seems that to get a high degree of the quality of lubrication for monotonic loading at low normal stresses, the following composition may be recommended: (1) the grease should be composed of low viscosity sulicone oil and an appropriate amount of fine fillers to increase the resistance against squeezing out. (2) a smooth surface should be facing the grease layer. On the other hand for monotonic loading at high normal stresses the following composition may be recommended. (1) the grease should be composed of high viscosity silicone oil and fine fillers also to increase the resistance against squeezing out. (2) a composition with which stress concentrations in the grease layer are reduced. For cyclic normal stresses $\bar{\sigma}_v$ Dow grease was found to be better because it shows less deterioration during decreasing $\bar{\sigma}_v$. However for cyclic normal stresses below $\bar{\sigma}_v$=50 kN/m^2 both kinds of grease used in this study seem unsatisfactory because the apparent friction angle φ becomes larger than 1 degree. For many cycles of shearing no clear conclusions can be drawn yet because the rate of deterioration of the quality of lubrication is not known.

DIRECT SHEAR TESTS ON LUBRICATION LAYERS BETWEEN TWO PLATENS

It could be expected that the resistance against squeezing out of a lubricant compressed between two parallel platens increases with the increase in filler content. However, it could also be expected that as a result the quality of lubrication would decrease as well. The following tests were performed to evaluate the effects of increased filler or powder content on φ. In this testing program the lubrication layer was not in contact with a sand mass but it was placed between two parallel flat surfaces to perform tests under simpler conditions.

Test material and test setup: Two kinds of grease (Silicone grease KS 63 G and Dow grease), two kinds of powders (PTFE and MoS_2) and mixtures of grease and powder with several values of powder to grease ratio were tested. The mean diameter of MoS_2 (Molybdenum Bisulfide) podwer is around 1～2 μm and the particles have an angular shape. The values of the weight ratios of the powder to the grease were selected as 0%, 10%, 30% and 60%, while only for the Dow grease-MoS_2 mixture the maximum powder ratio selected was 50%, because of its difficulty in mixing. In the following the powder to grease ratio will be used to indicate the composition of the mixtures. For example the mixture of PTFE and Silicone grease KS 63 G with a powder to grease weight ratio of 3 to 7 will be denoted as PTFE/KS 63 G (3/7). For most tests, the nominal initial thickness h_i was selected as

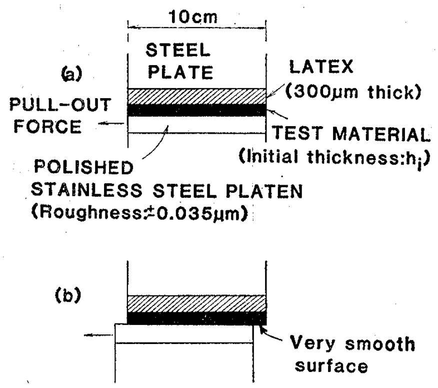

Fig. 15. Schematical diagrams showing direct shear test on lubrication layer placed between two platens (not scaled)

100 μm which was the minimum operationable thickness for obtaining a uniform layer of MoS_2/Dow (5/5). One test with PTFE/KS 63 G (6/4) was performed for $h_i = 300\ \mu$m. Test material was placed between a 300 μm thick latex disc and a polished stainless steel platen with a diameter of 10 cm (Fig. 15(a)). For each normal stress the consolidation time before the application of shear was 10 minutes with only a few exceptions. The direct shear apparatus shown in Fig. 6 was used. The horizontal displacement rate v was 0.5 mm/min except for one test (see Fig. 18). One cycle of direct shear was applied under a constant $\bar{\sigma}_v$ and such cycles were repeated with increasing $\bar{\sigma}_v$. The other testing procedures were similar to those described in the former section.

Test results and discussions: The test results are summarized in Figs. 16 through 20. The following points may be seen from these figures:

(1) For both kinds of grease the presently measured value of φ was less than for the cases in which the lubrication layer of type 1 was placed beneath the sand mass. In particular, the value of φ for Dow grease was only 0.06 degree when $\bar{\sigma}_v = 690\ kN/m^2$. It seems that these low values of φ for the grease may be due to the relatively uniform distribution of the normal stress and the shear stress in a grease layer placed between two rigid flat platens (Fig. 15(a)), when compared to the non-uniform distribution of these stresses in a lubrication layer in

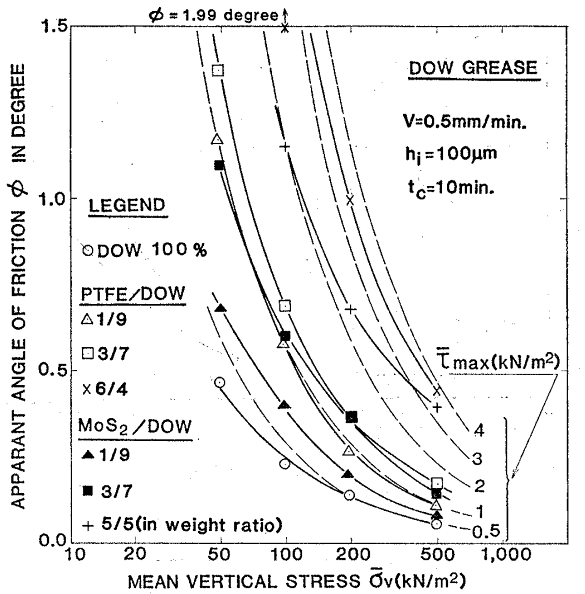

Fig. 16. Values of φ for Dow grease and its mixtures with powders

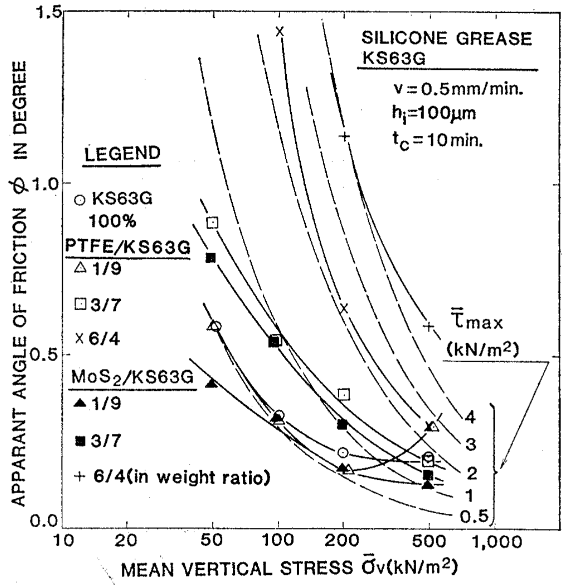

Fig. 17. Value of φ for Silicone grease KS-63 G and its mixtures with powders

contact with a sand mass (Fig. 7). In the latter case in the grease layer stress concentrations might occur near the points where the protruding sand grains are indenting the latex discs deeply.

It may be seen from Figs. 17 and 18 that except for the case of zero or low powder ratios with Silicone grease KS 63 G the values of maximum mean shear resistance $\bar{\tau}_{max}$ were almost independent of $\bar{\sigma}_v'$ resulting in strong dependency of φ on $\bar{\sigma}_v$. Probably,

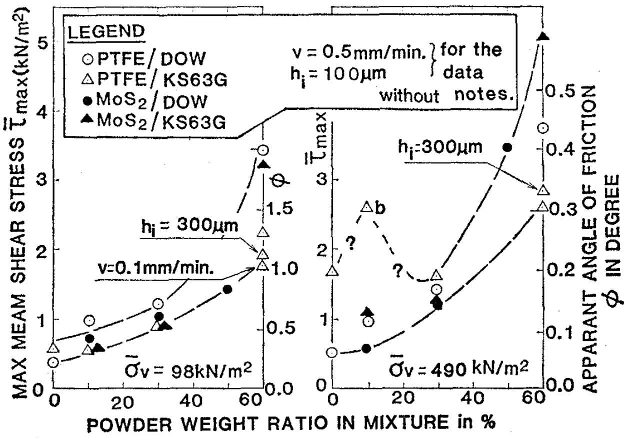

Fig. 18. Change in $\bar{\tau}_{max}$ and φ with increasing powder content

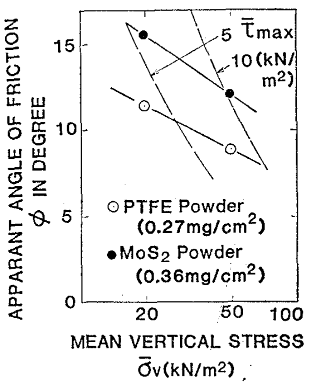

Fig. 19. Values of φ for pure powders (v=0.5 mm/min)

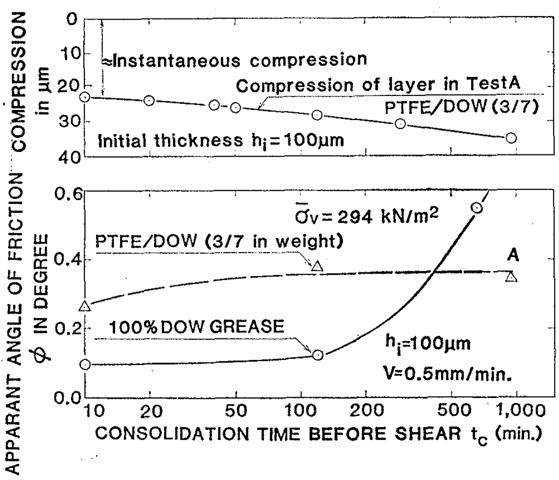

Fig. 20. Value of φ for sustained stress

in the cases of zero or a low powder ratio with Silicone grease KS 63 G, the test material will tend to be squeezed out under high vertical stresses $\bar{\sigma}_v$ (see Fig. 3(b)), resulting in the increase in $\bar{\tau}_{max}$ with the increase in $\bar{\sigma}_v$. It might also be expected that after the grease has been squeezed out and only one layer of fillers has been left the friction angle φ will tend to become somewhat constant with increasing $\bar{\sigma}_v$. The magnitude of this maximum friction angle φ might be dependent on the shape, the size, the interparticle friction and the relative distance of the filler particles. Performances with $\bar{\tau}_{max}$ being constant and independent of $\bar{\sigma}_v$ seem to indicate a viscous material. However, several other aspects of the behaviour of the mixtures with a high powder content during cyclic shearing were not in accordance with a viscous material, namely: (a) the mixtures behaved as rigid bodies as schematically shown in Fig. 15 (b) without showing any clear deformation inside the material, (b) no clear decrease in $\bar{\tau}_{max}$ was observed when the initial thickness of PTFE/KS 63 G (6/4) was increased from 100 μm to 300 μm (Fig. 18), (c) no clear decrease in $\bar{\tau}_{max}$ occurred when the value of v was decreased from 0.5 mm/min to 0.1 mm/min (Fig. 18). The authors have no clear explanation in physical terms of the observed aspects of the behaviour of these mixtures.

(3) There was a clear increase in φ or $\bar{\tau}_{max}$ with the increase in powder content (Fig. 18), except for the case of Silicone grease KS 63 G and its mixture with a low powder content. Such observations are consistent with the fact that φ and $\bar{\tau}_{max}$ of thin powder layers of PTFE and MoS_2 were very high (as shown in Fig. 19). Note that for a thin powder layer not $\bar{\tau}_{max}$ but φ is somewhat independent of $\bar{\sigma}_v$.

(4) When the content of powder was sufficient to prevent squeezing out under the present vertical stress range of $\bar{\sigma}_v$ the quality of lubrication did not deteriorate severely under sustained pressure (see Fig. 20). Applying an elapsed time of 10 minutes and a $\bar{\sigma}_v$ of 294 kN/m^2, the friction angle φ for PTFE/Dow (3/7) was more than twice as large as that for Dow grease. However, the value of φ for this PTFE/Dow (3/7) during a sustained pressure of 16 hours did not change severely, namely from about 0.25

degree to about 0.35 degree, while φ for Dow grease increased up to 0.55 degree after 12 hours. In fact, compression of sample A with PTFE/Dow (3/7) during this 16 hours was negligible, as shown in Fig. 20. The instantaneous compression of sample A may be due to the compression of air bubbles involved.

In summary, application of shear stress soon after the application of the vertical stress shows an increasing apparent friction angle φ with increasing powder content. But the initially low friction angles of grease deteriorate when longer times between the application of normal stress and shear stress are applied, while the friction angles of mixtures with high powder content do not deteriorate severely. Further researches will be needed to know the effects of the characteristics of the filler (size, shape, material, mass ratio with respect to base oil or others) on the quality of lubrication.

The best lubricant under pressure might be a mixture of high liquid oil and a filler with spherical particles, sufficiently small compared with the sand and probably made of a material with a low interparticle friction. The powder (filler) content should not be too much but just enough to either prevent any squeezing out of the lubricant or to get a sufficient dense packing of the one remaining layer of filler particles near the stress concentrations where the protruding sand grains are indenting the latex discs deeply. Which of both cases will be more attractive will depend on their respective frictional properties.

TRIAXIAL COMPRESSION TESTS WITH LUBRICATED ENDS

Because insufficient lubrication of the end platens in triaxial compression tests would result in an increase in compressive strength with decreasing height to diameter ratio of the sample, a series of triaxial compression tests on samples of Toyoura sand having different height to diameter ratios was performed under an effective confining pressure of 98 kN/m². The nominal value of the diameter was 7 cm for all specimens. The nominal values of the heights were 2 cm, 4 cm, 7 cm and 15 cm. Therefore, the height to diameter ratio h/d varied between 2 to 7 and 15 to 7. The following cautions were taken to increase the accuracy of testing: (1) The cap was fixed to the loading piston. (2) Both the cap and the pedestal were enlarged (7.5 cm in diameter). These were machined from stainless steel alloy. The surfaces facing the sand sample were polished to a roughness of $\pm 0.035\,\mu$m and lubrication layers were made directly on these surfaces. The compositions for lubrication were similar to those used for the direct shear test (see Fig. 7). Type 2 composition was used for Silicone grease KS 63 G and type 1 composition was used for Dow grease. The thicknesses of the applied grease layers were of the order of 50 μm. In order to obtain smooth lubrication layers each layer was preloaded under $\bar{\sigma}_v=6.7$ kN/m² for about one hour. At the centers of cap and pedestal drain holes with a diameter of 1 cm were applied. The friction caused by the porous stones placed in the drain holes prevented the lateral movement of the specimen under triaxial compression. (3) The surfaces of cap and pedestal were set to be parallel to each other. (4) The heights of samples were adjusted by using pedestals having different heights. Therefore the initial locations of the caps were identical for all the tests. (5) Dense to medium dense samples were prepared by pluviating dry sand through air. The top surfaces of samples were made parallel to the surfaces of the cap and pedestal and flat and smooth by scraping the sample surfaces with a thin wooden plate. (6) The stress paths during sample preparation and the following isotropic consolidations were carefully controlled so as to maintain always an isotropic stress conditions at the top of the specimen. (7) The dimensions of air-dry samples were measured at a vacuum of 5 kN/m² in order to prevent large bedding errors in measured heights. The effects of such errors become larger with the decrease

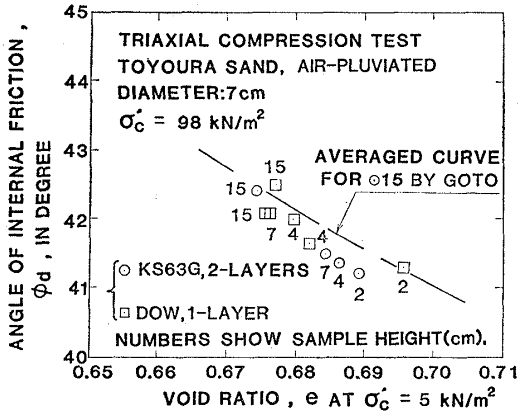

Fig. 21. Results of triaxial compression tests on samples having different heights and the same diameter

in sample height. The measured Mohr-Coulomb friction angles were plotted against the void ratios which were measured at a confining pressure of $5\,\mathrm{kN/m^2}$ (Fig. 21). (8) The loading piston was guided with two low-friction linear motion bearings at the top plate of triaxial cell. It was found that the friction in the bearings was very small (0.6 N at most under the application of large thrust forces). The axial load was measured outside the triaxial cell with a load cell. The sealing against pressurized cell air was achieved by placing a gap of about 0.01 mm between the inside wall surface of the bearing house and the loading piston along a length of 5 cm between two bearings. (9) The samples were saturated and backpressurized with a back pressure of $98\,\mathrm{kN/m^2}$ in order to measure the volumetric strains rather accurately. The volume changes were determined by measuring the height of water in a burette with a low capacity differential pressure transducer (Tatsuoka, 1980). (10) The effective radial stress was directly measured as a differential pressure between the cell water pressure and the pore water pressure to an accuracy of $0.1\,\mathrm{kN/m^2}$ with a high capacity differential pressure transducer.

The regulated air pressure was applied to the surface of the cell water which was located at the top of the cap on the sample. Before the start of triaxial compression first 60 minutes of drained isotropic loading at an effective stress of $98\,\mathrm{kN/m^2}$ was applied. It might be expected that during this period the pressure in the base oil of the greases might have been reduced by consolidation. This consolidation might have been similar to the consolidation before the application of shear in the direct shear test on the lubrication layer in contact with the sand mass.

An axial displacement rate $\dot{\varepsilon}_a$ of 0.2%min was applied. Then, the maximum radial strain $(\dot{\varepsilon}_r)_{max}$ would be of the order: $(\dot{\varepsilon}_r)_{max} = -(\sigma'_1/\sigma'_3)_{max}/(2K) \times \dot{\varepsilon}_a = -5/(2\times3)\times 0.2\%/\mathrm{min} = -0.17\%/\mathrm{min}$ in which $(\sigma'_1/\sigma'_3)_{max}$ is the principal stress ratio at the peak strength and K is the dilatancy coefficient for this test condition. Therefore the maximum horizontal radial expansion rate would be about $0.17\%/\mathrm{min} \times 35\,\mathrm{mm} = 0.06\,\mathrm{mm/min}$ at the periphery at the peak strength. The value of σ'_1 at failure would be around $500\,\mathrm{kN/m^2}$. It was expected from the results shown in Figs. 13 and 14 that under such conditions (v=0.06 mm/min or less and $\bar{\sigma}_v = 500\,\mathrm{kN/m^2}$ the angle of friction φ at end boundaries would be 0.3 degree or less. The test results are summarized in Fig. 21. The solid curve shown in Fig. 21 is the averaged curve obtained by Goto (1982) for the case of samples having a height of 15 cm and ends lubricated by type 2 composition with Silicone grease KS 63 G. It may be seen that the value of φ does not tend to increase with decreasing height to diameter ratio. Up to the peak strengths at least, smooth lateral spreading was observed at the top and bottom of sample irrespective of the height of sample. However, after the peak strength for the highest samples with a nominal height to diameter ratio of 15/7 a larger degree of bulging was observed than for the other samples.

From these findings it is clear that for the applied order of stresses and Toyoura sand a good quality of lubrication is obtained by using a layer of 50 μm of Dow grease and only one latex disc with a thickness of 300 μm. This conclusion seems somewhat different from that by Bishop and Green (1965). By using a medium coarse Ham

River sand with a d_{50} of around 0.25 mm and a latex membrane having a thickness of 0.22 mm for end lubrication Bishop and Green (1965) obtained an increase in φ of around 1 degree with the decrease in height to diameter ratio from 2 to 1 and a further increase of around 1.5 degree with the decrease in height to diameter ratio from 1 to 0.5 under a confining pressure of around 275 kN/m^2. Possible reasons for such increase in φ may be a smaller ratio of membrane thickness to mean diameter t/d_{50}, a larger normal stress at failure and a much longer preloading time before the start of triaxial compression.

CONCLUSIONS

From the experimental results the following conclusions can be drawn for the lubrication of the end platens on fine sand:

(1) In cyclic loading tests with long duration sufficient quality of lubrication cannot be obtained using oil as the lubricant. Oil with a sufficiently high viscosity to provide good lubrication during one cycle of loading will certainly be squeezed out during a number of cycles. Both kinds of grease as considered could not be squeezed out completely; It was clearly observed after the test that at least for Silicone grease KS 63 G always one layer of filler of the grease was left.

(2) Multiple-layer lubrication layers give slightly better lubrication during first loading than single lubrication layers but with the multiple layers significant extra bedding errors are introduced, which are caused mainly by the Poisson's effect in the compressed latex discs.

(3) For a Silicone grease KS 63 G layer with an initial thickness of about 50 μm, the apparent friction angle φ is rather independent of shear rate between 0.1 and 50 mm/min when φ is less than around 1 degree for a mean normal stress range $\bar{\sigma}_v$ between 27 kN/m^2 and 672 kN/m^2 and for consolidation times before shearing less than 60 minutes.

(4) During initial loading for a normal stress of 150~670 kN/m^2 and for a shear rate of 0.2 mm/min a grease layer with an initial thickness of about 50 μm consisting of Dow grease gives slightly better lubrication than with Silicone grease KS 63 G. In this range the optimum 'friction angle' φ is smaller than 1 degree. For lower normal stresses the 'friction angle' is larger, due to viscous effects, for instance at a normal stress of 5 kN/m^2 it can be of the order of 10 degree for first loading. In the normal stress range between 150 kN/m^2 and 670 kN/m^2 and for initial loading the composition with one grease layer between two latex discs gives the highest quality of lubrication.

(5) In the stress range below 50 kN/m^2 the effect of preloading to about 650 kN/m^2 causes severe deterioration of the quality of the lubrication. The possible deterioration of the lubrication under cyclic loading of long duration has not been determined so far.

Future research on this subject should be aimed at obtaining a good lubrication layer also for both low normal stresses and cyclic loading of long duration. Such improvement might be obtained by using a grease composed of highly viscous oil and a sufficient amount of filler with spherical particles, sufficiently small compared with the sand and made of a material with a low interparticle friction. The filler content should be enough to either prevent any squeezing out of the lubricant or to get a sufficient dense packing of the one remaining layer of the filler particles near the stress concentrations where the protruding sand graines are indenting the latex discs deeply.

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