5.5 Introduction to Rock Sliding tests

The results obtained from wood sliding tests made it imperative to investigate similar behaviour for rock sliders, if later vibration tests were to be understood fully. However, rock discontinuity shear strength is different in many respects to that of wood. Of greatest importance is the change of strength with displacement that is often seen for rock. Such changes were not apparent in wood sliding tests. Therefore, before investigating variations in strength for rock sliders due to weight or geometry of blocks, it was necessary to understand how angle of sliding changes with displacement.

Rock surfaces that have a high roughness normally show a decrease in strength as asperities are worn down and rock flour generated. It is found that after a certain displacement a minimum strength is reached. This minimum strength is termed the residual strength.

Rock discontinuities with smooth surfaces are more variable in their behaviour than those with rough surfaces; often there is either a slight increase or drop in shear strength, Coulson (1972), Richards (1973).

The experiments described below were designed to investigate:-

i) The variation of shear strength with displacement for ground rock surfaces;

ii) The effect of normal load and geometry of block on the angle of sliding.

5.6 Angle of Sliding versus Displacement for four rock types

Apparatus and Sample Preparation

Experiments were carried out using the same apparatus as described in section 5.2. Thin sliders of rock were cut to fit onto the base of the top block that weighed 5.2 N, and had an internal angle, α, of 38°. It was found that the best method of attachment was by means of double sided sellotape.

The rock sliders were ground using a 220 grade diamond wheel. The upper surface of the basal block was similarly ground. The prepared surfaces were very flat, with a roughness component dependant upon the porosity and grain size of each individual rock type.

Four rock types were chosen on account of their homogeneity and small grain size relative to the size of the sliding surfaces.

Descriptions of each rock type - Darleydale Sandstone, Delabole Slate, Portland Limestone and Permian Sandstone are given in Appendix 4. The surface finish of each rock type is presented as a Talysurf profile and an assessment made of the factors controlling shear strength for each surface.

Experimental Method

Each slider was weighed, measured and attached in turn to the base of the metal top block. (of same basal dimensions as the slider). In each test the assembled block was placed on the surface of the basal block, with its leading edge 16 cm from the lower end of the basal surface (see fig.5.1). The position of the top block was fixed by means of pencil marks drawn on the basal surface at the rear and sides of the top block. The inclined plane was then raised slowly to an angle at which the top block slid. This angle of sliding was noted. Rock surfaces were examined before and after sliding with a binocular microscope. In one case a detailed study of the surfaces was made before and after sliding, using microphotography and an electron scanning microscope. The amount of flour generated was rarely enough to be collected and analysed in detail but qualitative descriptions were made.

After the first sixteen centimetres of sliding, the basal plane was taken back to horizontal and the top block replaced in the same position as before. In some tests rock flour was allowed to accumulate throughout but in others the rock flour was removed between runs by means of a camera lens blower and a fine hair brush.

As the behaviour of rock surfaces under the conditions described above became clear, the procedure was varied in certain tests by:-

i) removing rock flour from surfaces after a residual angle of sliding had been reached for surfaces with accumulated rock flour.

ii) allowing rock flour to accumulate after a residual had been reached for cleaned surfaces,

iii) reversing blocks so that edges that were formally at the rear of the slider became the leading edges at the front of the slider,

iv) placing worn sliders on fresh basal surfaces, and

v) placing fresh sliderson worn basal surfaces.

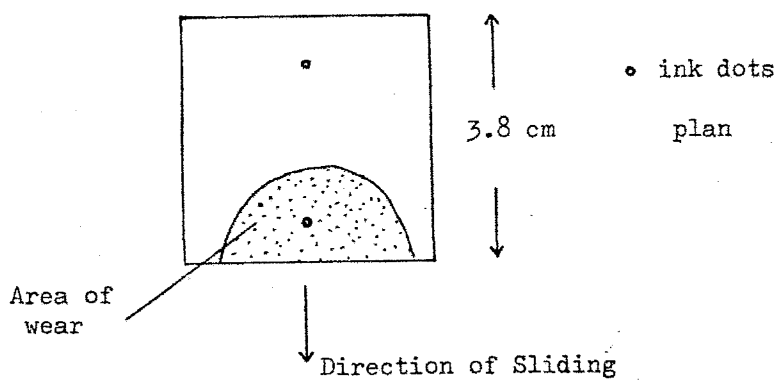
Observations of the area of wear were made directly for each test and also by means of drawing pencil lines on the basal surface and measuring the areas removed by wear during one test. Each test differed in its procedure from other tests and for this reason the tests are described and discussed separately with conclusions finally drawn from all tests results.

Darleydale Sandstone

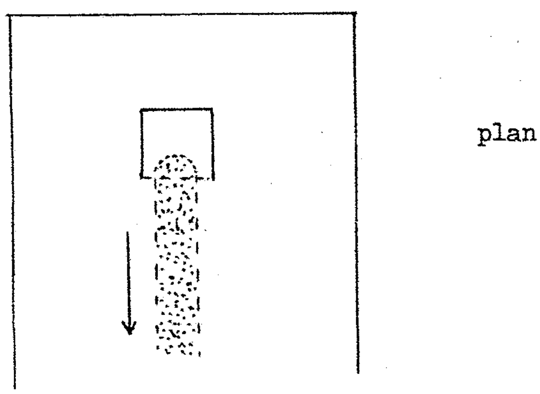
Four sliding tests were carried out using Darleydale Sandstone sliders.

TEST 1

In this test rock flour was accumulated during repeated sliding. The results are plotted in figure 5.14 and show a drop in the angle of sliding from 32° to 27° with increasing displacement. The residual value was first reached after about 80 cm of sliding (after 5 runs) and became stable (± 0.5°)after 144 cm of sliding. The area of wear could be easily distinguished by the accumulation of rock flour and was concentrated at the front and centre of the slider.



The basal block showed a corresponding line of wear down slope.



Two small ink dots on the slider surface (see above diagram) were used as reference points for observation of wear. The rear dot was

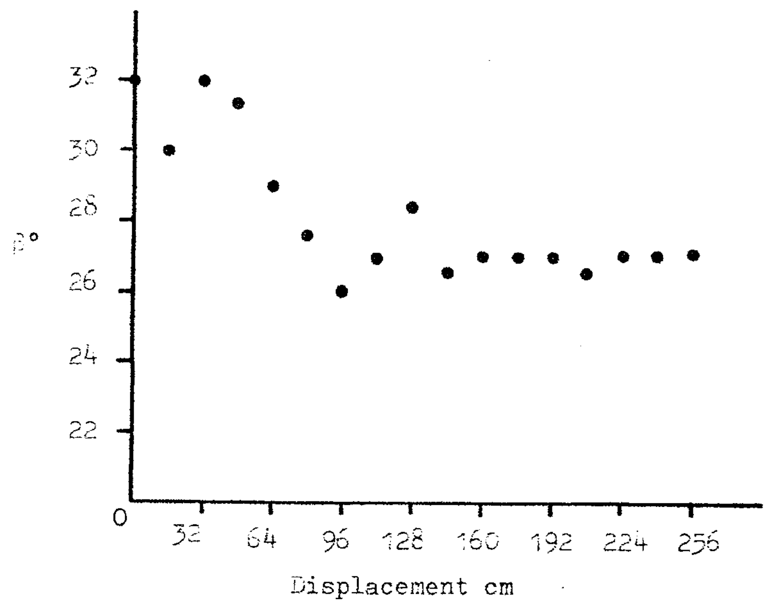


Figure 5.14 Angle of Sliding versus displacement
Darleydale Sandstone - Flour accumulated
TEST 1.

found to be completely clean after 256 cm of displacement with no evidence of damage. The front dot in contrast was almost covered by fine rock flour. Quartz grains at the front of the slider which were clean and fresh before sliding appeared frosted and coated with fine flour at the end of the test.

After 48 cm of sliding the area of wear extended approximately 1.5 cm back from the front edge of the slider. This area grew toward the rear of the slider at later stages of the test and extended 2 cm from the leading edge after 256 cm sliding.

The basal length (ℓ) of the top block is 3.8 cms. Referring to Appendix 1, figure A.1.1, case 3, the length over which stress is acting, x,

$$x = \frac{3}{2}(\ell - h \tan \beta)$$

knowing that $\frac{\ell}{h} = \tan \alpha$

then $x = \frac{3\ell}{2}\left(1 - \frac{\tan \beta}{\tan \alpha}\right)$ 5.2

Substituting for ℓ, α and β (lowest value) after 48 cms sliding and 256 cms sliding, we obtain values for

x of 1.49 cms for $\beta = 30°$

and 2.14 cms for $\beta = 26°$

The agreement between measured area of wear and calculated length of slider over which stress is acting is very good, and suggests that the area of wear is controlled by the stress distribution as presented in Appendix 1.

It is not clear, however, why the area of wear should be curved in outline rather than rectangular. It will be seen though that other tests showed a similar shaped area of wear. Some, however, showed wear on the two leading corners rather than centre, and Permian Sandstone characteristically showed a rectangular area of wear.

Conclusions from Test 1

1) The angle of sliding decreases from a peak value to a stable residual value with displacement for rock flour covered surfaces.

2) The area of wear extends further back from the leading edge of the slider as the angle of sliding decreases.

3) The extension of the area of wear agrees well with that predicted by the theory for stress distribution on an inclined plane, presented in Appendix 1.

TEST 2

Test 2 using Darleydale Sandstone consisted of four parts, (see figure 5.15)

a) Rock flour was accumulated until a residual angle of sliding reached, (as in Test 1).

b) The sliding block was then reversed and slid several more times, still allowing rock flour to accumulate.

c) After 480 cm total displacement rock flour was removed and sliding was continued with rock flour being removed between each run until a residual angle of sliding was reached.

d) After 736 cm displacement, rock flour was again allowed to accumulate until a constant sliding angle was reached.

Section (a) of this test confirmed the results obtained from Test 1. The angle of sliding decreased from a peak of 32° to a residual of 26.5°, first reached at, and stable from, 80 cm displacement. This corresponds to a drop from 32° to 27° in Test 1.

The area of wear differed from that seen in Test 1 although it extended backwards by approximately the same length.

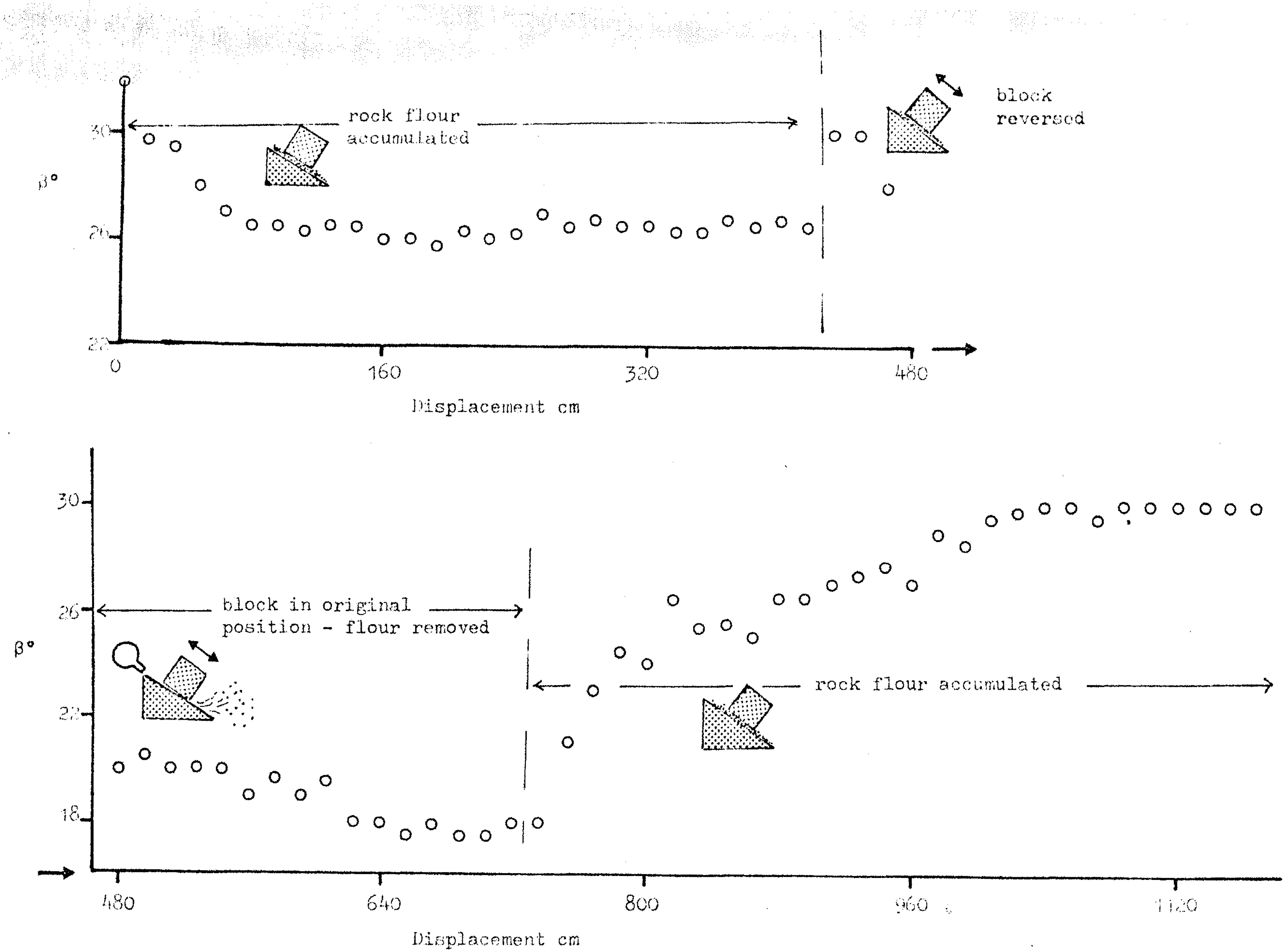
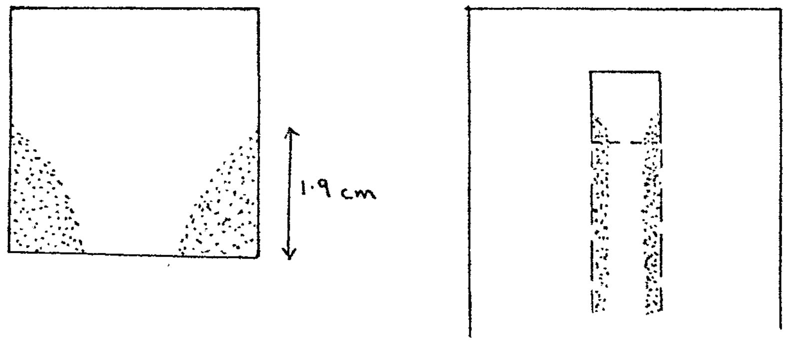


Figure 5.15 Angle of sliding versus displacement
Darleydale Sandstone - TEST 2



The area of wear was concentrated at the leading corners of the slider and parallel wear lines were seen on the basal surface. This variation in area of wear is probably due to slight non-planarity of the surfaces.

After 416 cm displacement, (the residual angle of sliding had been constant for over 300 cm), the sliding block was reversed. This was to determine whether a surface has a unique shear strength or whether direction of sliding must be defined. The angle of sliding was found to jump from 26.5° to 30°. The experiment was continued for 48 cms with the block in this reversed position and a sharp decrease in the angle of sliding was seen similar to the initial drop seen in section (a) of this test and in Test 1. It is probable that if the experiment had been continued with the block reversed, a similar drop to a residual angle of sliding as that seen for the first 416 cm sliding would have resulted. After this stage of the test wear was observed on the two corners of the slider previously not worn. The rise in angle of sliding seen at the start of section (b) was due to fresh areas of slider making contact. The fact that the angle of sliding only rose to 30° rather than the peak angle of 32° seen at the start of the test is due to the fresh sliding surface sliding on a worn base.

Section (c). After 480 cm of sliding, rock flour was removed from the surfaces and the block replaced in its original position. The angle of sliding immediately dropped to 20° and decreased after repeated sliding to a residual value of 17.5° to 18.0°.

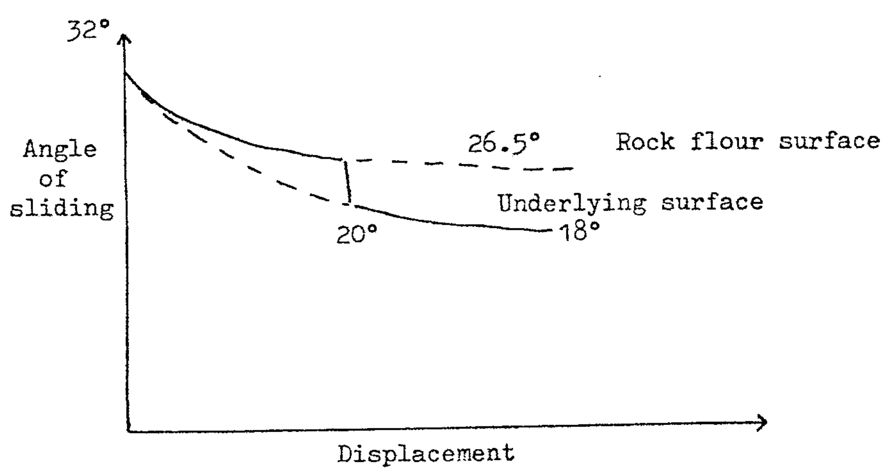
These results illustrate two points.

1) That after large displacements, the presence of rock flour results in a higher angle of sliding than for a clean surface. This is shown by a drop of 6.5° in the angle of sliding solely due to the removal of flour.

2) After removal of rock flour, the angle of sliding continues to drop to a lower residual even though the angle of sliding has been constant for over 300 cm for rock flour covered surfaces.

One possible explanation for this is that the surfaces underlying the rock flour were protected from damage by the rock flour, and then when exposed were subjected to further damage.

An alternative explanation is that the underlying surfaces were being damaged, even though they were covered by a rock flour that had developed a residual angle of sliding.



Hence, the removal of rock flour may simply have revealed the final stages of an attrition process that had been continuing beneath the rock flour mantle throughout the test.

The most probable explanation for the continued drop in angle of sliding when gouge is removed, is that the area of contact stress extends further backwards from the front of the slider for the block at an inclination of 20° than at 26.5°.

From equation 5.2

for $\beta = 26.5°$ $x = 2.06$ cm

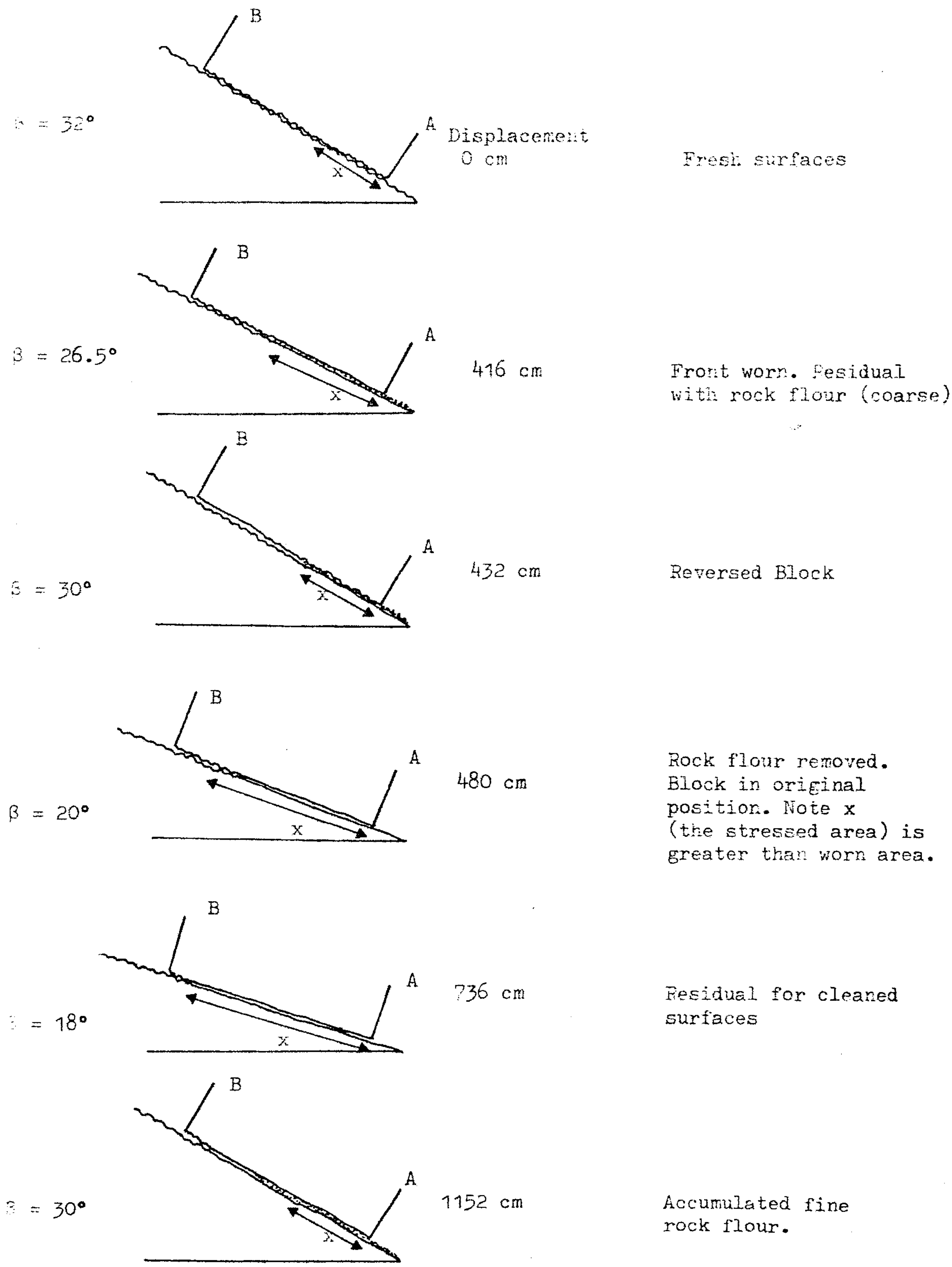
for $\beta = 20°$ $x = 3.04$ cm

Therefore, by sliding at 20°, (the angle of sliding being largely controlled by the worn, highly stressed front region of the slider), an area of fresh slider was brought into contact, (under relatively low stress compared to the front of the block), and the drop in sliding angle from 20° to 18° resulted from the gradual wearing down of the resistance to sliding offered by this fresh contact area.

The fact that this drop was only 2° illustrates that the shear strength of the surface was largely controlled by the highly stressed region toward the leading edge of the block.

Section (d). The accumulation of rock flourafter 736 cm displacement resulted in an increase in the angle of sliding. This increase was initially steep then gradually diminishing to a stable value of 30°. The rock flour generated during this increase in sliding angle was much finer grained than that generated during the first section of this test. The angle of sliding for this surface was, however, 3.5° higher than the residual reached in the first section.

The results of this whole test are illustrated diagramatically in figure 5.16.



x in all cases calculated for β from equation 5.2

Figure 5.16 Diagrammatic history of Test 2
Darleydale Sandstone

Conclusions from Test 2

1) The conclusions from test 1. are confirmed.

2) As would be expected, the direction of sliding of a block is important in determining shear strength as fresh areas of contact control strength as the orientation of the top block is changed.

3) Surfaces with rock flour removed have lower residual strengths than surfaces covered in rock flour.

4) Shear strength for surfaces covered in fine rock flour can be greater than for surfaces covered with coarser flour.

TEST 3

Test 3 was designed to investigate further the difference in angle of sliding between rock flour covered surfaces and surfaces from which rock flour is removed.

Again this test consisted of four sections, (figure 5.17).

a) Rock flour was removed until a constant residual angle of sliding was reached.

b) The worn slider was slid upon a fresh part of the basal surface.

c) With the block replaced in its original position rock flour was accumulated until a constant angle of sliding was obtained.

d) Rock flour was again removed from the surface.

In section (a) a reduction in the angle of sliding from 32.5° to 12.5° occurred over a sliding distance of 320 cm. The residual angle is much lower than that obtained during tests 1 and 2 for surfaces with accumulated rock flour, (12.5° compared to 26.5°). It is also lower than that obtained in section (c) of test 2 in which rock flour was

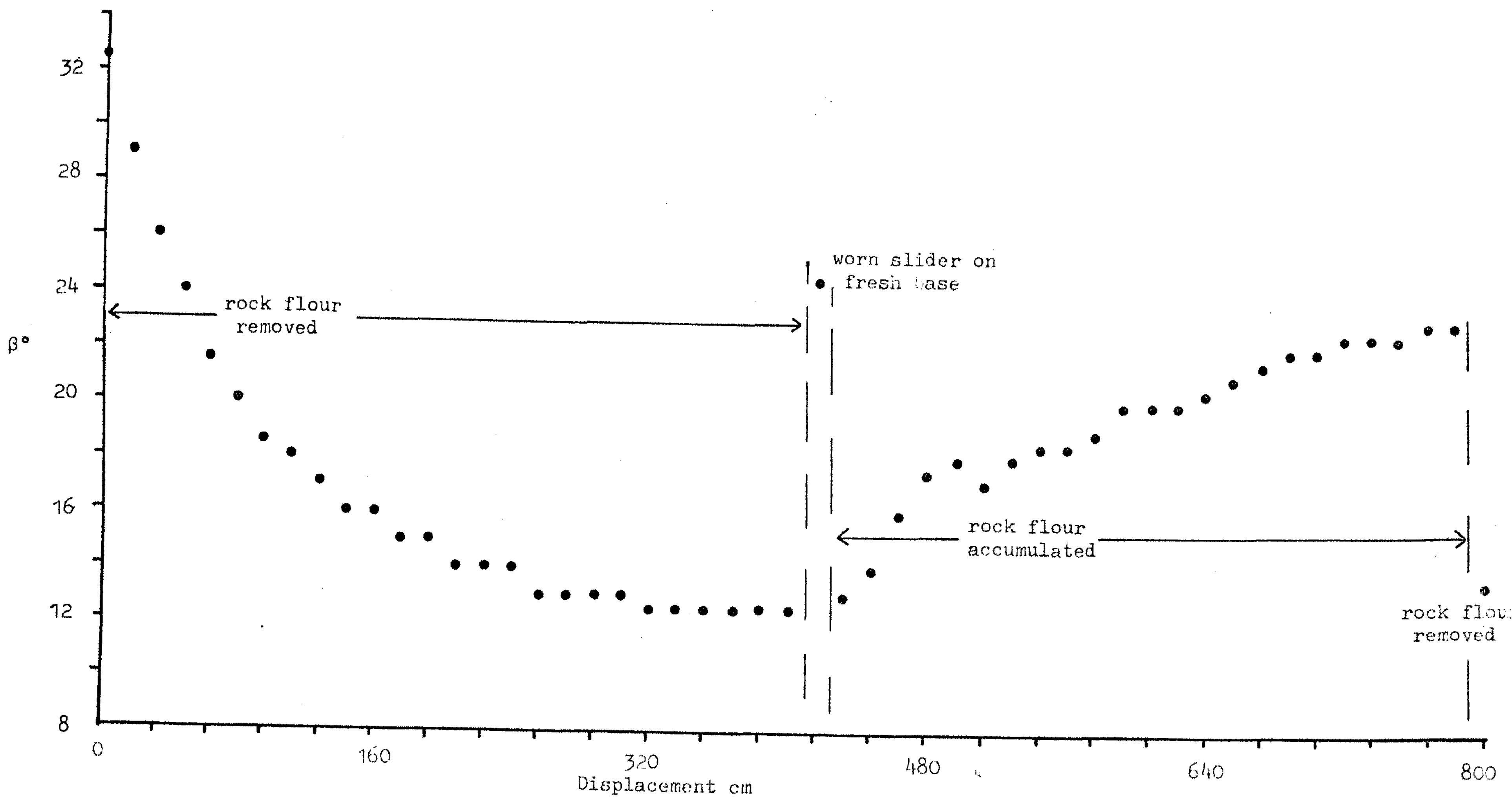


Figure 5.17 Angle of sliding versus displacement

Darleydale Sandstone - TEST 3

removed. (12.5° compared to 18°).

After 400 cm sliding, the clean worn slider was placed on a fresh part of the basal surface and was found to slide at an angle of 24.5°.

In section (c) the slider was replaced in its original position and rock flour accumulated during repeated sliding. As had been seen in the latter part of test 2 the angle of sliding increased sharp ly and then more slowly to a stable angle. In this test the stable angle was 23° comparing to an equivalent angle of 30° in test 2. The corresponding rise in angle was, however, similar, 10.5° for this test compared to 12° in test 2, which suggests that the final stable angle is dependant upon the residual sliding angle for cleaned surfaces which in turn is dependant upon the sliding history of the surfaces.

In section (d), after a stable angle had been reached, rock flour was again removed from the surfaces and the angle of sliding found to be 13.5°. This shows that the rise in angle observed in stage (c) was almost entirely due to the accumulation of very fine rock flour. Although examination of the sliding surfaces from tests 1 and 2 had revealed the areas of wear, being areas of rock flour accumulation, no distinction could be made for cleaned surfaces at the end of test 3 between the contact and non-contact areas using a binocular microscope (X40).

<u>Conclusions from Test 3</u>

1) A very low residual angle of sliding was obtained by repeated sliding of Darleydale Sandstone surfaces, rock flour being removed after each run of 16 cm.
2) Assuming that the shear strength of rock surfaces may be represented by an equation of the form $S = N.\tan \phi + k$; then ϕ, the basic angle of friction for Darleydale Sandstone must be less than 12.5°.
3) That attrition of the surfaces must still have been occurring at

angles of sliding of 12.5° may be concluded from the fact that rock flour was accumulated in the later rise in angle of sliding.

4) Comparison of results from test 3 with the equivalent sections of test 2 leads to the conclusion that the residual angle of sliding reached is dependant upon the history of sliding of the surfaces.

Presumably, different surface finishes are produced by sliding, which affect the ability of the surfaces to cause further attrition.

TEST 4

Test 4 again involved the sliding of Darleydale Sandstone surfaces from which rock flour was removed after each run of 16 cm. The test was conducted to confirm the results from test 3, section (a) and to make detailed observation of the processes involved in the marked decrease in strength with displacement.

Surfaces were examined before sliding by means of a binocular microscope. 3 areas, one at the front, one in the middle and one at the rear of the top slider, were located with coloured ink dots. The area at the front was photographed at magnifications of up to X25, and then these photographs annotated according to observations made using the microscope. Drawings were made of the areas around the ink dots.

An electron scanning microscope was also used to examine the general surface finish before and after sliding. The preparation of a specimen for this work involved coating the surface with gold. As this process might have altered the frictional properties of the surface, pre-sliding photographs were taken of the reverse side of the slider. It was hoped that general differences might be noticed post-sliding e.g. rounded grains, ploughing marks etc.

Pencil lines on the sliding surfaces were used to indicate the extent of the area of wear throughout the test. It was expected that the sections of line removed by wear would correspond to the area of stress as predicted by theory. (Appendix 1).

The angles of sliding measured after incremental displacements of 16 cm are plotted in figure 5.18. The rate of drop in angle of sliding with displacement is very similar to that obtained in test 3 although the residual angle reached in this test was 2.5° higher. Presumably this variation was due to minor differences between the surfaces used in each test.

It had been intended to collect rock flour after every third run to compare the weight and grain size of flour produced at different stages during the test. It was also intended to analyse the samples to investigate possible preferential removal of certain mineral types. In practice, the amount of rock flour generated was too small to allow such an analysis to be made. One sample was collected after 128 cm sliding and was found to contain a large proportion of whole grains of quartz. Examination of surfaces during the early part of the test also indicated that large pieces of mineral grain were being removed from the surfaces. A further 272 cm of sliding, however, only generated a very small amount of fine dust.

The extension back from the leading edge of the slider of the area of wear as indicated by the removal of pencil lines, was smaller than predicted by equation 5.2. Previous tests (1 and 2) had shown, however, that the extension of the area of wear as indicated by accumulation of rock flour agreed well with that predicted by equation 5.2. Presumably, in this test,wear over the area of low contact stress was

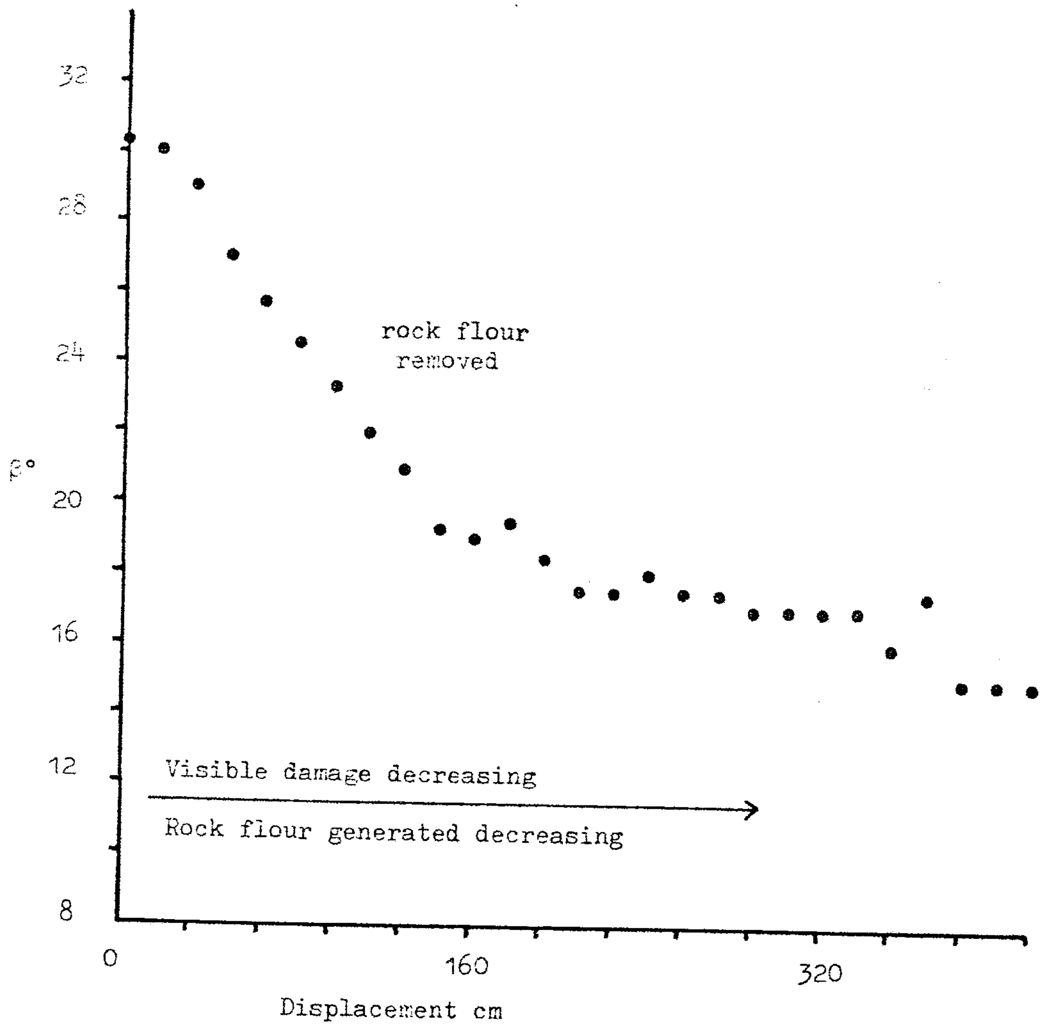
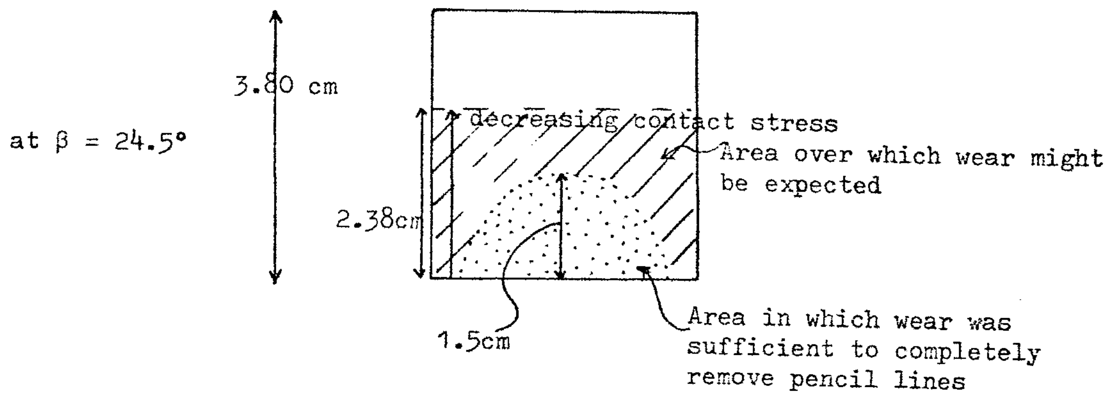


Figure 5.18 Angle of sliding versus displacement
Darleydale Sandstone - TEST 4

not severe enough to result in the complete removal of pencil lines.



Examination during the test, of the areas located by ink dots, showed that no visible damage occurred at the centre or rear of the slider. Several grains were removed, however, from the area around the dot toward the leading edge of the slider. All observed damage occurred in the first 112 cm of sliding.

Comparison of electron scanning microscope photographs of fresh and worn areas indicated no significant differences in surface texture.

On completion of this test, blocks of different weights to that used during the test were attached to the same worn slider; these composite blocks were slid upon the same basal surface. The original block weighed 5.19 Newtons. The use of a wooden block weighing only 0.07 Newtons resulted in a jump from the residual angle of 15° to a peak of 31°. The angle of sliding then dropped to 17° after 4 runs. Another block weighing 0.15 Newtons was then attached to the slider and the angle of sliding found to be 22°, dropping to 17° on sliding a second time. These results illustrate that once movement has occurred the physical characteristics of a surface that determine the strength for a certain load and load distribution may not be of the same importance in determining the strength of the same surface for different loads and load distributions.

Conclusions from Test 4

1) The very rapid drop in angle of sliding with displacement for surfaces from which rock flour was removed, observed in test 3, was confirmed.

2) The average grain size of rock flour generated during sliding decreases with displacement.

3) The visible damage to surfaces decreases with displacement. Whole grains are removed from the surfaces during the initial stages of sliding.

Conclusions from Darleydale Sandstone Sliding Tests

1) It has been shown that the initial angle of sliding for ground surfaces of Darleydale Sandstone using a metal block of internal angle 38° and weight 5.19 Newtons is approximately 32°.

2) The peak angle of sliding decreases to a residual angle with displacement.

3) The residual angle reached is dependant upon whether or not rock flour is allowed to accumulate between the surfaces.

4) Different residual angles of sliding are obtained for surfaces under similar conditions if their sliding histories are different.

5) The extension of the area of wear backwards from the leading edge of the slider as indicated by areas of rock flour accumulation agrees well with that predicted for contact stress distribution.

6) The initial steep drop in sliding angle with displacement is accompanied by the plucking of large mineral grains from the surfaces. Later stages of sliding produce much finer grade rock flour.

7) The factors involved in the frictional resistance for a surface under a certain normal load, may not be the same as those controlling strength for other normal loads.

8) Angles of sliding obtained for surfaces reflect the shear strength of a defined area of wear. Alteration of the distribution of stress by, for example, reversing the block on an inclined plane, will result in a different angle of sliding for the surfaces due to different areas of contact.

9) It may also be concluded that the angle of sliding reflects the shear strength of an area of wear rather than individual asperities. This conclusion stems from the fact that it is unlikely that the top block will always be replaced in exactly the same position and, therefore, different grains will be in contact in each run. However, the shear strength of the surface as reflected by the angle of sliding, varies with displacement in a precise manner. This implies that the shear strength at any displacement is the same no matter which grains are in contact and represents the strength of a large area rather than of individual grain contacts.