Portland Limestone

Two tests were carried out using sliders and a basal block of Portland Limestone. These tests were designed to investigate similar behaviour to that seen for Darleydale Sandstone with regard to

1) a decrease in angle of sliding with displacement, and
2) a dependance of the residual angle reached on the presence of rock flour between the surfaces.

TEST 1

The results of this test are plotted graphically in figure 5.19.

The first stage involved repeated sliding of the block, allowing rock flour to accumulate. The initial peak sliding angle was much higher for Portland Limestone than for Darleydale Sandstone, 38° compared to 32°. This angle dropped to a residual of 34.5° after 64 cm of sliding and remained constant (± 0.25°) for a further 192 cm of sliding. Rock flour was then removed from the surfaces and sliding continued with the removal of rock flour after each run of 16 cm. The angle of sliding dropped rapidly to a residual angle of 16.5°.

After 480 cm of sliding rock flour was allowed to accumulate and the angle of sliding increased to a residual of 19°.

TEST 2

In Test 2 (figure 5.20), rock flour was removed between each run during the first stage of the test. A drop in angle of sliding from 38° for fresh surfaces to a residual of 19° ± 1° occurred over the first 144 cm of sliding. After 288 cm displacement rock flour was allowed

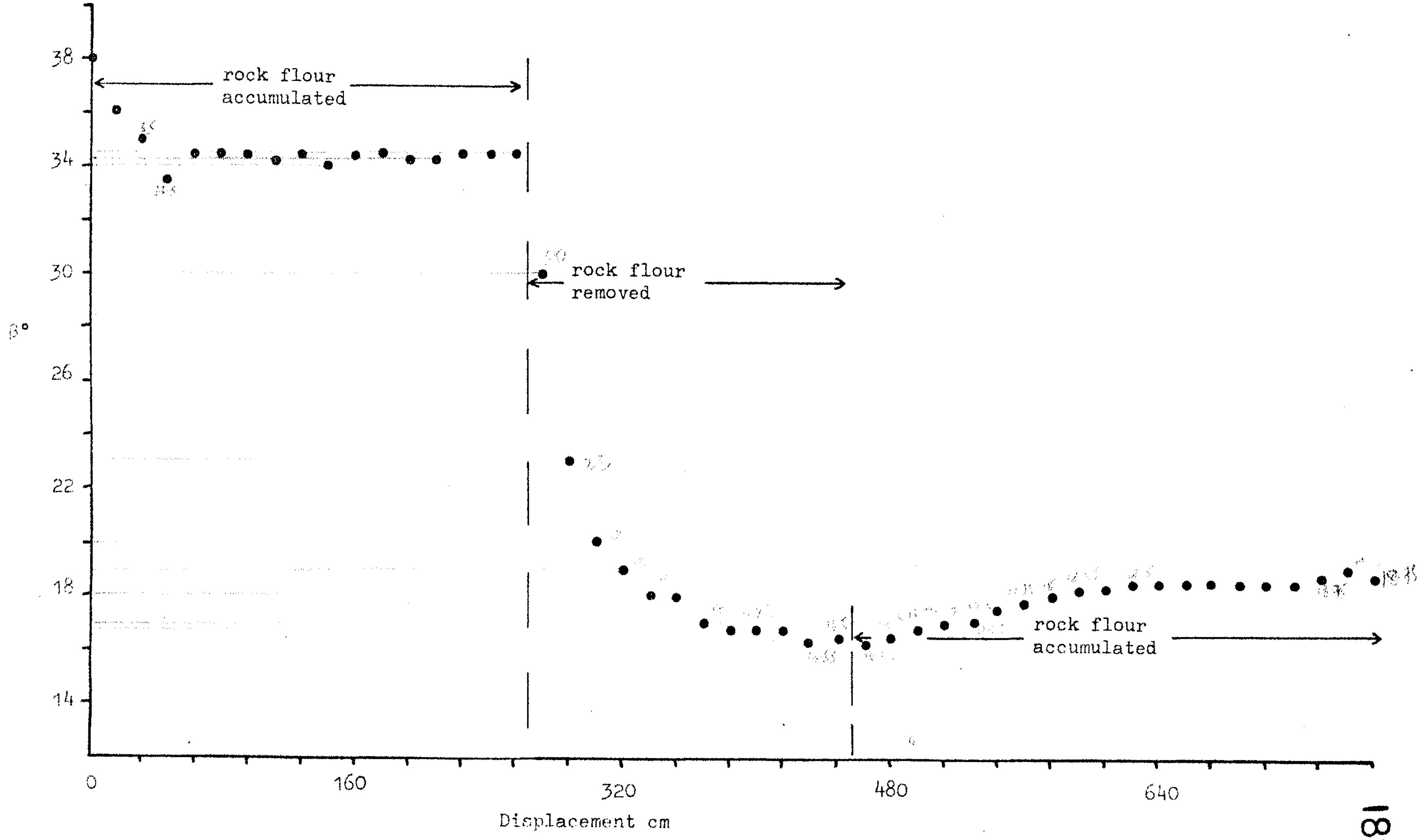

Figure 5.12 Angle of sliding versus displacement. Portland Limestone - TEST 1.

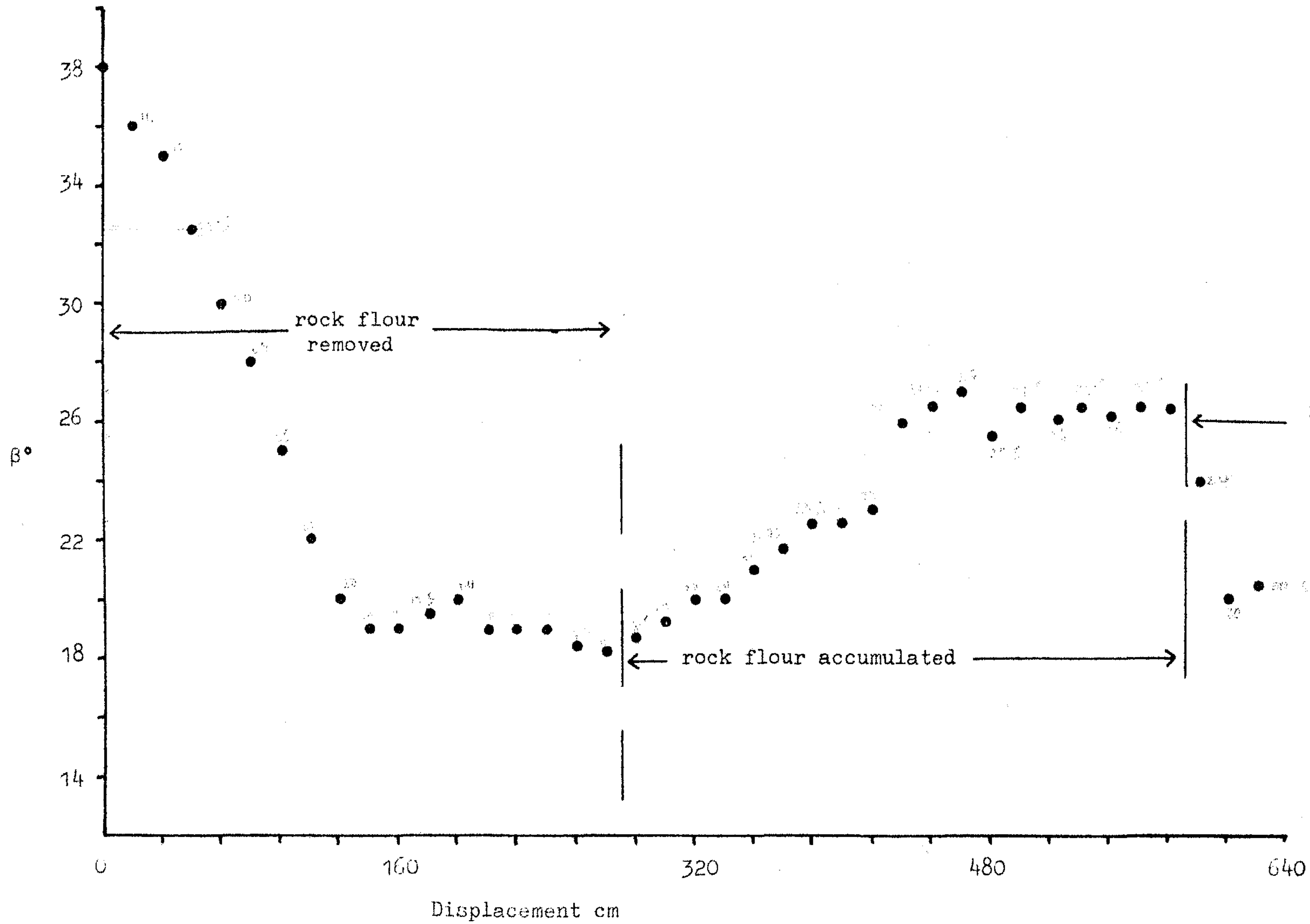

Figure 5.20 Angle of sliding versus displacement - Portland Limestone - TEST 2

to accumulate between the surfaces and the angle of sliding was seen to increase to a stable residual value of 26.5° ± 0.5° after 448 cm sliding. Rock flour was again removed after 576 cm and the angle of sliding dropped to 20°.

Conclusions from Portland Limestone Tests

1) Ground surfaces of Portland Limestone show similar angle of sliding/displacement relationships to those seen for similar surfaces of Darleydale Sandstone. Lower residual angles of sliding are observed for surfaces from which rock flour is removed than for those with accumulated rock flour between the surfaces.

2) Further evidence is given for the conclusion that the residual angle reached is dependant upon the previous sliding history of the surfaces. In test 1 the drop to a residual angle after rock flour was removed resulted in an angle of sliding 2.5° lower than that reached in Test 2 where rock flour was removed from the start of the test.

   Corresponding tests for Darleydale Sandstone (see figures 5.15 and 5.17) show an opposite relationship between sliding history and residual angle reached.

Differences between the final residual angle reached by allowing rock flour to accumulate also reflect the different sliding histories. Presumably the surfaces after the early stages of test 1 (figure 5.19) were so worn that when flour was allowed to accumulate, the surfaces were unable to generate enough rock flour to significantly raise the angle of sliding. In comparison the surfaces in test 2 (figure 5.20) after 288 cm sliding were still sufficiently interlocking to cause attrition and generate relatively large amounts of rock flour.

Delabole Slate

Similar tests to those carried out using Portland Limestone, were conducted using ground surfaces of Delabole Slate.

TEST 1

The results from test 1 are given in figure 5.21. The peak angle of sliding for fresh surfaces, 29.75° decreased to a residual angle of 22° for surfaces coated with rock flour after 256 cm sliding.

After 352 cm sliding, rock flour was removed and the angle of sliding dropped to a residual of 17°. After 448 cm, rock flour was again allowed to accumulate, the angle of sliding rising again to 20.5°. The rock flour produced throughout this test, consisted of very fine white dust, the majority being produced in the early stages of sliding.

TEST 2

The results in figure 5.22 show an initial peak angle of sliding of 31°, decreasing to a residual of 16° over displacement of 384 cm for rock flour free surfaces. Rock flour was accumulated after 400 cm sliding, and the angle of sliding was seen to increase in two stages to a stable residual angle of 22°.

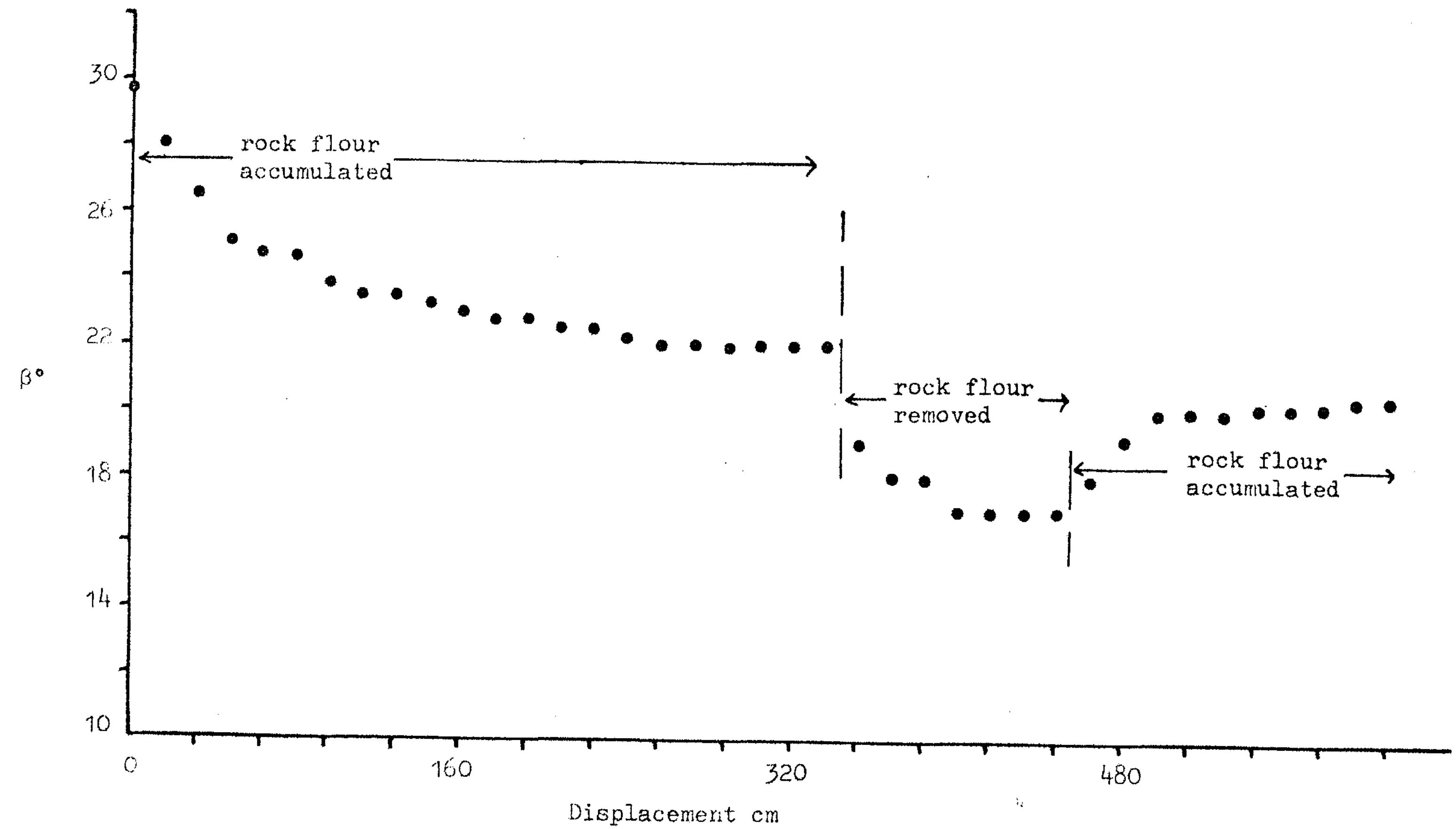

Figure 5.21 Angle of sliding versus Displacement. Delabole Slate - TEST 1

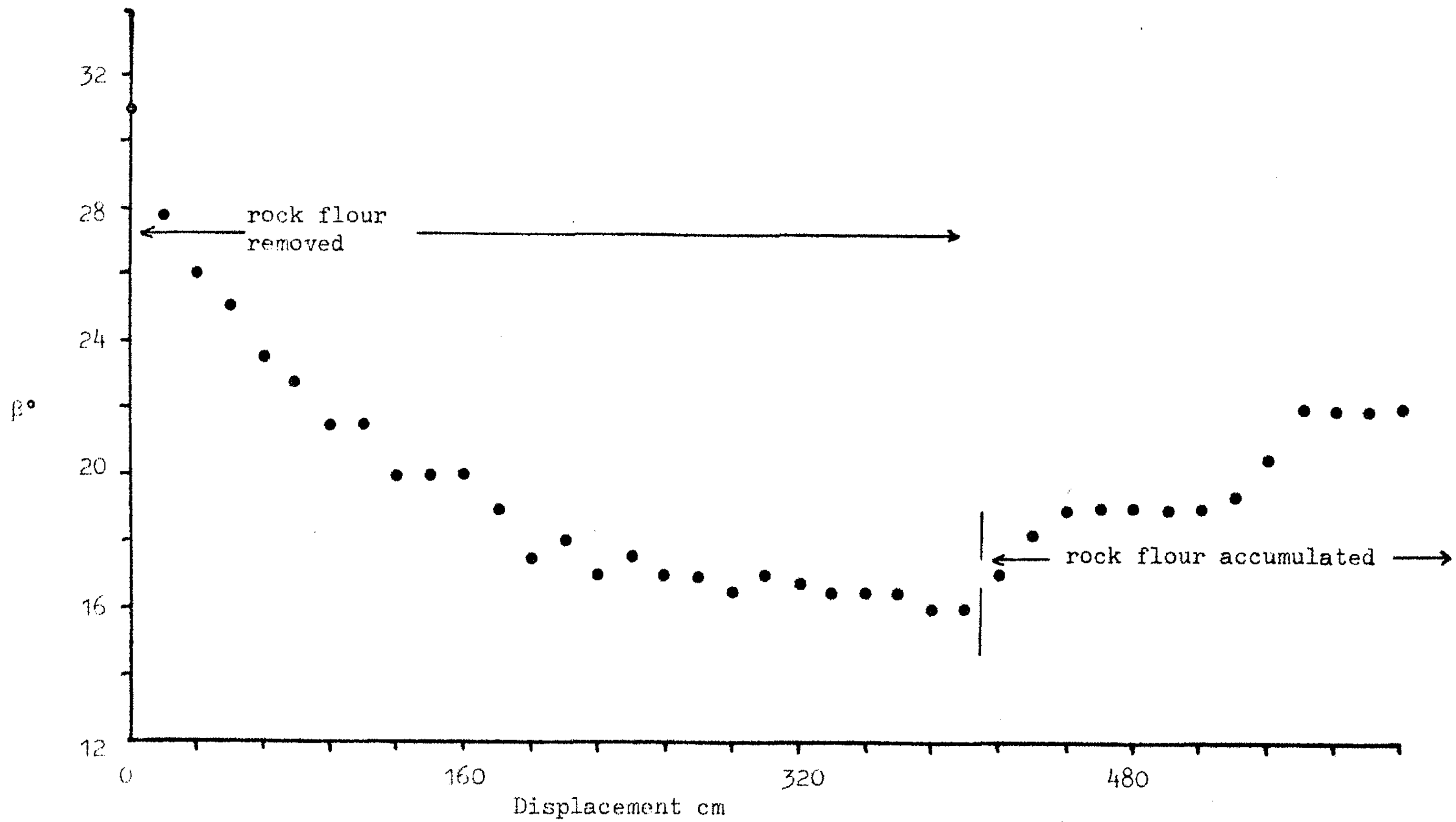

Figure 5.22 Angle of sliding versus displacement. Delabole Slate - TEST 2

Conclusions from Tests on Delabole Slate

1) The fundamental difference between the shear strengths of clean worn surfaces and those of worn surfaces with accumulated rock flour observed in all other tests, was also observed in these tests on Delabole Slate.

2) Sliding history appears to be of less importance for Delabole Slate in determining the final residual angle for cleaned surfaces, there being a difference of only 1° in the angle of sliding obtained at the corresponding sections of each test.

The secondary rise in angle of sliding with rock flour accumulation, however, shows similar effects to that seen for Portland Limestone. The rise in angle for surfaces from which previously rock flour had been removed from the start of the test was significantly greater than for the corresponding part of test 1. It is interesting that the final residual angle reached in test 2 is the same as that for rock flour covered surfaces in the first part of test 1.

The two tiered rise in angle of sliding in test 2 may be due to:

a) an initial immediate strengthening due to the accumulation of fine flour,

b) a secondary steep rise due to the increasing ability of the surfaces to produce rock flour.

A diagrammatic history of tests 1 and 2 on Delabole Slate is given in figure 5.23.

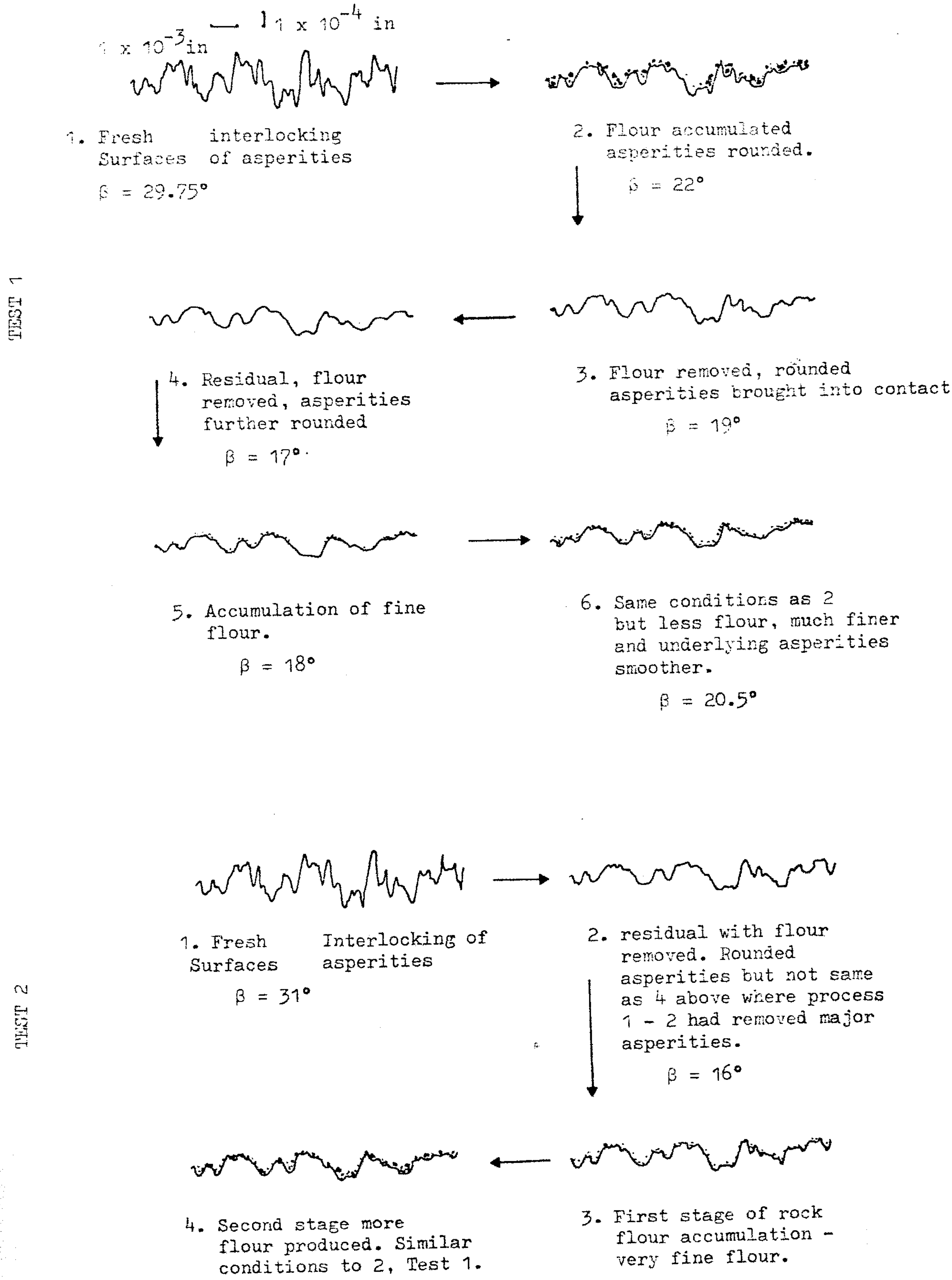

Figure 5.23 Diagrammatic illustration of frictional behavipur of Delabole Slate.

Permian Sandstone

Two inclined plane sliding tests were carried out using surfaces of Permian Sandstone. This rock type was the coarsest grained of those tested and was far more friable than the other rocks. (Appendix 4).

TEST 1

This test involved four stages of sliding.

a) rock flour was accumulated for the first 256 cm of sliding;

b) rock flour was removed for the next 160 cm of sliding;

c) rock flour was again accumulated during the next 80 cm; and

d) rock flour was removed for the final 32 cm of sliding.

The results of this test are given in figure 5.24. It is clear that these results differ in several respects to those obtained for other rock types.

In stage (a) of the test, an initial angle of sliding of 32.5° was measured. The following change in angle of sliding with displacement was much more random than for previous tests. The angle of sliding varied between 32.5° and 28° with one aberrant measurement of 38°. This variable angle of sliding was accompanied by the accumulation of a large amount of rock flour, much more than in tests with other rock types.

In stage(b)of the test, removal of rock flour resulted in a decrease in the sliding angle to a stable value of 25°. However, whereas in all other tests the first removal of rock flour resulted in an immediate drop in the sliding angle, in this test the first run with flour removed (after 256 cm displacement) was at a similar angle as had previously been recorded for surfaces with accumulated rock flour. It was only in subsequent runs that the angle of sliding was reduced.

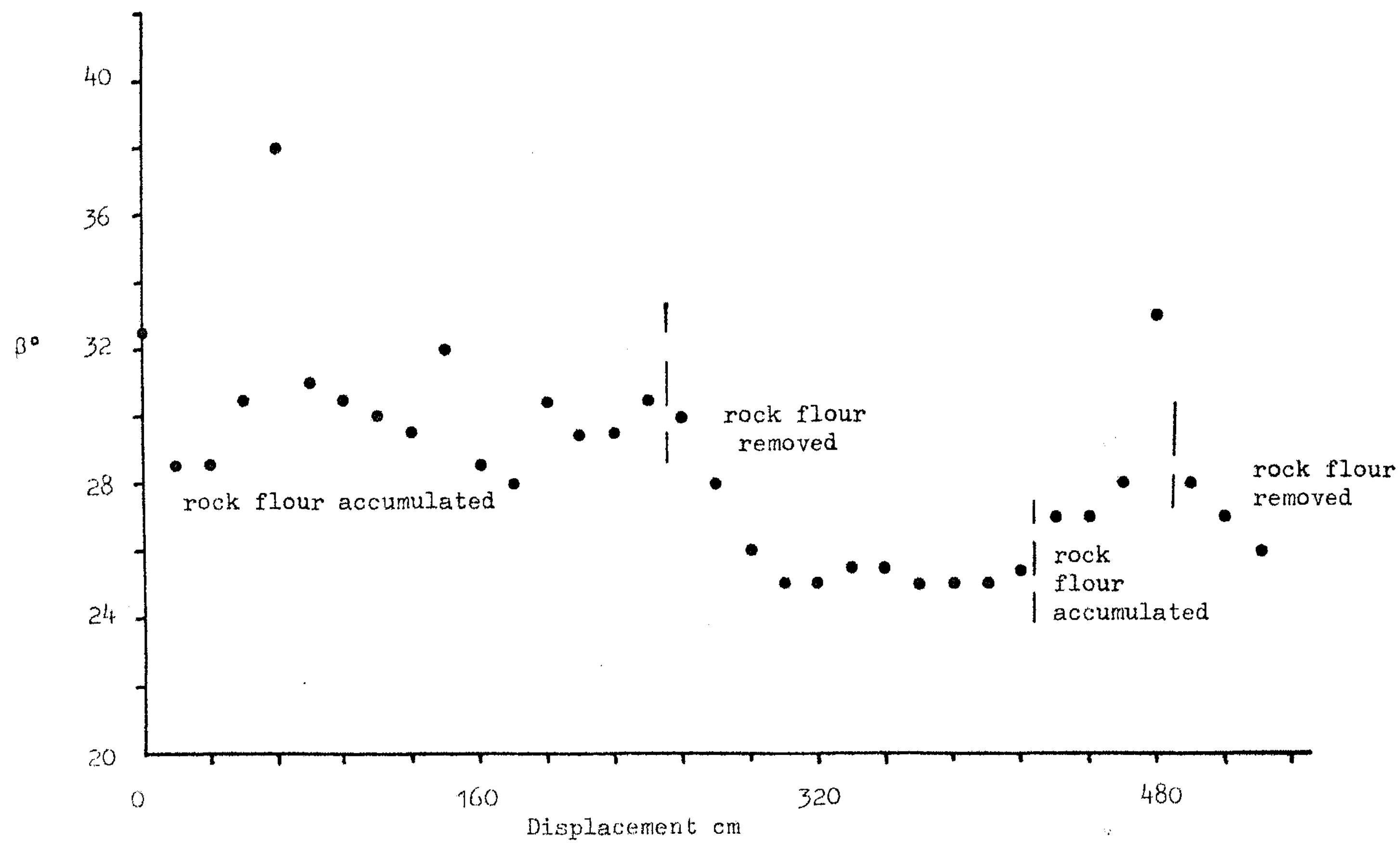

Figure 5.24 Angle of sliding versus Displacement - Permian Sandstone - TEST 1

After 416 cm of sliding rock flour was again accumulated and the angle of sliding was seen to increase with displacement. Another aberrant angle of 33° was recorded, however, during this stage. A final removal of rock flour resulted in a decrease in the angle of sliding.

TEST 2

In test 2, rock flour was removed between each run of 16 cm. The results are given in figure 5.25. Again these results differ from those obtained from other rock types in similar tests. Whereas other tests under similar conditions had shown clearly defined reductions in the angle of sliding with displacement to constant residual values, the Permian Sandstone surfaces showed no such drop. The angle of sliding varied between 32° and 28°. The top slider was weighed before and after testing and the rock flour collected from both surfaces. The loss of weight of the slider was approximately 1.6% i.e. 1 grain in 60. This loss of weight equalled almost exactly the weight of rock flour, which implies that nearly all wear was occurring to the top slider. The area of wear extended approximately 0.9 cms towards the back of the specimen i.e. approximately 1/4 of the slider surface. The area of wear was rectangular, extending the whole width of the slider. For all tests with other rock types the area of wear had been restricted to the front centre or leading corners of the slider. The slider was approximately 30 grains thick which implies the removal of a layer 2 grains thick on average over the area of contact. Presumably, a greater proportion would have been removed towards the leading edge of the slider, however, where contact stresses were higher.

It is difficult to explain why in test 2 no drop in the angle of sliding was observed for surfaces from which rock flour was removed

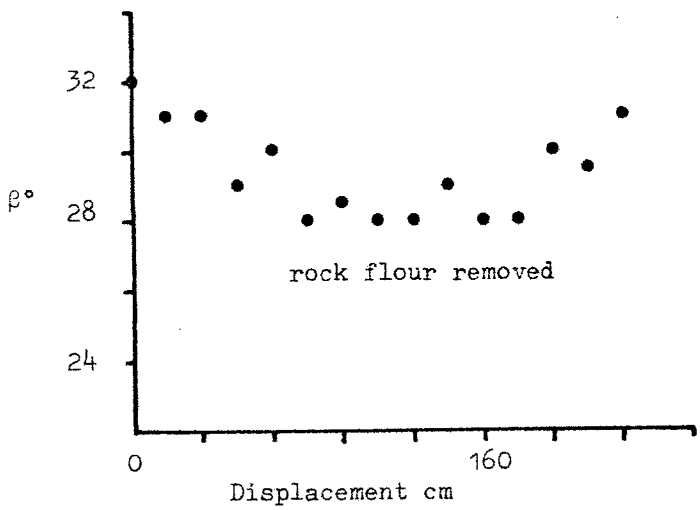

Figure 5.25 Angle of sliding versus Displacement - Permian Sandstone TEST 2

whereas in the first test a drop in strength was seen when rock flour was removed from surfaces upon which rock flour had been accumulating for 256 cm sliding. It has been noted in appendix 4 that the strength of Permian Sandstone surfaces is probably controlled by the weakly cemented nature of the rock. Individual mineral grains are much less likely to become worn, consisting mainly of rounded intact quartz grains. In other rock types the bonding between grains is much stronger and wear of the surfaces is likely to occur by the progressive rounding and polishing of mineral grains set firmly into the intact rock. In the case of Darleydale Sandstone many of the grains are fractured and will partially fragment rather than be wholly plucked from the surface.

The process involved in the wear of Permian Sandstone surfaces is therefore, one in which whole, weakly cemented, mineral grains are plucked from the surfaces. In test 2 the removal of rock flour at the end of each run simply exposed a fresh surface of weakly cemented grains. There is little difference between the strength of a fresh surface and one covered in rock flour.

However, in the first test, a drop in $\beta°$ did occur on the removal of rock flour. A possible explanation for this is that during the first 256 cm of sliding when rock flour was accumulated, the weaker cemented grains in the underlying surfaces were loosened. When the rock flour was removed, the exposed surfaces consisted of slightly better cemented grains and the following reduction in β was due to the modification of these better cemented grains which remained fixed in position. This explanation is illustrated diagramatically in figure 5.26.

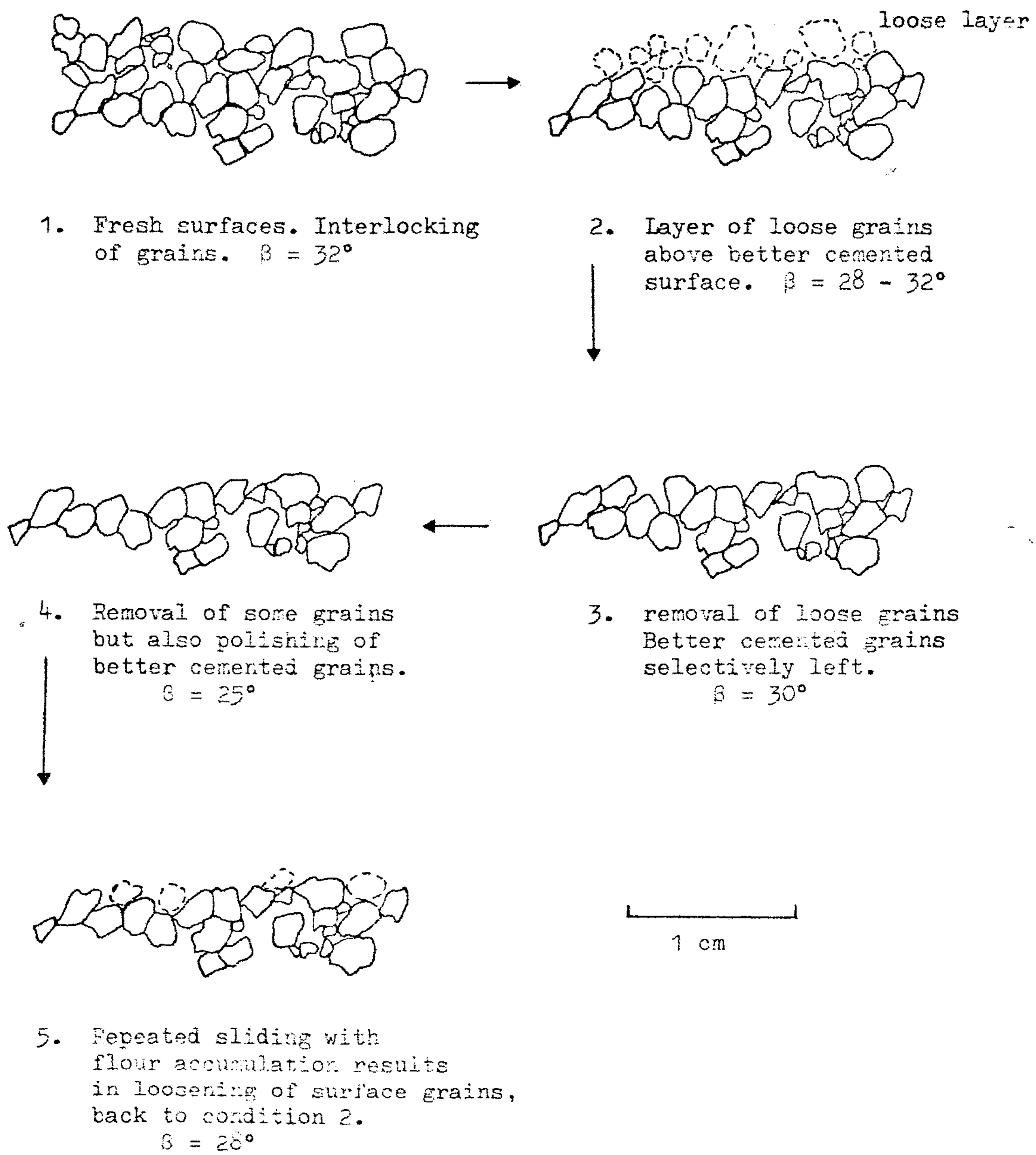

Figure 5.16 Diagrammatic illustration of frictional behaviour of Permian Sandstone, Test 1.

Conclusions to Section 5.6

1) It may be concluded that the inclined plane sliding test is reliable and produces repeatable results for the angle of sliding of ground rock surfaces. It is a particularly useful test for studying the process of wear with displacement. Difficulties might arise, however, in testing rougher surfaces, as the low loads used may be resisted by fairly small surface aberrations.

2) In order to carry out tests to investigate the relationships between angle of sliding, block geometry and normal load for rock surfaces, as reported in Section 5.4 for wooden sliding surfaces, it is clear that displacement must also be considered. The angle of sliding, β, was found not to alter with displacement for wood and there was therefore, no problem in using the same wood surfaces several times. For rock it is necessary to use a fresh top slider and basal surface for each test.

3) The fact that area of wear reflects distribution of stress has been seen for all rock types. However, minor variations in planarity of surfaces for the three less friable rock types, Darleydale Sandstone, Portland Limestone and Delabole Slate, resulted in the area of wear being restricted to the leading centre of the slider or to the front two corners.
The tests on Permian Sandstone showed that the area of wear extended across the whole width of the top slider as would be expected from the analysis given in Appendix 1.
Evidently the relatively large amount of wear occurring was enough to obscure any non-planarity effects seen for the other three rock types.

4) The results for all four rock types under similar conditions are summarised in table 5.3. It is clear that the three less friable

TABLE 5.3

Stage of Test \ Rock Type	Darleydale Sandstone	Portland Limestone	Delabole Slate	Permian Sandstone
A) Initial angle of sliding Average	31.7°	38°	30.4°	32.3°
B) Residual β for accumulated rock flour Average	26.8°	34.5°	22°	No Residual
A - B Drop to Residual	4.9°	3.5°	8.38°	No Drop
C) Residual following removal of flour from B	17.5°	16.5°	17°	25°
B - C Drop to Residual	9.25°	18.0°	5.0°	-
D) Residual β flour removed from start Average	13.75°	19°	16°	No change
C - D Difference	3.75°	-2. 5°	1°	-
E) Residual after accumulation of flour from C	30°	19°	20.5°	28°
F) E - C rise	12.50°	2.5°	3.5°	3.0°
G) Residual after accumulation of flour from D	23°	26.5°	22°	-
H) G - D Difference	9.25°	7.5°	6°	-
F - H	2°	-5.0°	-2.0°	-

rock types show similar behaviour although individual results differ. All show lower residual angles of sliding for worn, cleaned surfaces than for worn surfaces covered in rock flour, but individual results apparently depend on rock type and previous history of sliding. The results for Permian Sandstone are fundamentally different, and reflect the weak bonding between grains for this rock type and hence difficulty in producing a stable surface in which individual grains may be modified.

5.7 Inclined Plane Sliding tests using Rock Surfaces Weighted by Blocks of different geometries and Weights

The experiments using wooden blocks, described in section 5.4, indicated a relationship between the angle of sliding and mass and geometry of the sliding block. The test program described below was carried out to investigate similar relationships for sliders of rock.

Procedure

A set of 32 different blocks was prepared. These blocks consisted of four different materials cut to 8 different height: length ratios. The dimensions and weights of these blocks are giv en in table 5.4.

Ground sliders of Darleydale Sandstone were individually weighed and measured.

Each block from table 5.4, was then in turn attached to a rock slider, and then placed in position 1, edge forward, on a freshly ground base of Darleydale Sandstone. The plane was then gradually tilted until sliding occurred as described in previous sections. Sliding was repeated for 11 runs on each slider with rock flour allowed to accumulate throughout the tests. At the end of 176 cms sliding, as a measure of the amount of wear caused by each block, each slider was removed and attached to block M4 and slid for two more runs of 16 cm.

Tests were also carried out with blocks in position 2 (corner forward).

Results

The results of individual tests for blocks in position 1 are given in appendix 5 (figures A5.1 - A5. 22). The majority of these results show a drop from a peak angle of sliding to a residual angle of sliding. Anomolous results occurred occasionally with the lighter blocks. At

Wooden Blocks				
Block No.	h	b	w	α
W1	8.67	3.80	65	23.7
W2	7.29	3.80	58	27.5
W3	6.38	3.80	50	30.8
W4	4.69	3.80	37	39.0
W5	3.37	3.80	26	48.4
W6	2.97	3.80	23	52.0
W7	1.76	3.80	14	65.2
W8	0.88	3.79	7	76.9

Darleydale Sandstone Blocks				
Block No.	h	b	w	α
DS 1	8.67	3.84	291	23.9
DS 2	7.20	3.82	239.5	28.0
DS 3	6.45	3.80	212.5	30.5
DS 4	4.69	3.82	156	39.2
DS 5	3.55	3.82	118	47.1
DS 6	3.04	3.82	99	51.5
DS 7	1.89	3.81	63	63.6
DS 8	0.89	3.82	29	76.9

Araldite Blocks				
Block No.	h	b	w	α
A1	8.73	3.82	155	23.6
A2	7.42	3.82	132	27.2
A3	6.44	3.82	115	30.7
A4	4.75	3.81	84.5	38.7
A5	3.45	3.81	61.5	47.8
A6	3.02	3.81	54	51.6
A7	1.85	3.81	33	64.1
A8	0.89	3.81	15.5	76.9

Steel Blocks				
Block No.	h	b	w	α
M1	8.61	3.80	975	23.8
M2	7.38	3.80	830	27.2
M3	6.35	3.80	717.5	30.9
M4	4.70	3.80	529	39.0
M5	3.40	3.80	382.7	48.2
M6	3.00	3.80	336.5	51.7
M7	1.72	3.80	193	65.7
M8	0.88	3.80	97	77.0

h = height, cm $\pm$ 0.01 cm

b = breadth, cm $\pm$ 0.01 cm

w = weight, gm $\pm$ 0.5 gm

α = internal angle, degrees.

Table 5.4 Block Dimensions and Weights.

such light loads the angle of sliding is more dependant upon minor variations in the surfaces. The results from tests using heavier blocks show much less scatter.

The internal angle of each block/slider combination was calculated by the method given in Appendix 6. These calculated values are given in Appendix 5. Graphs of internal angle versus angle of sliding (figure 5.27) show little relationship between the two parameters. Contouring these graphs according to the mass of each block similarly shows no relationship. It was hypothesised in section 5.4 that the behaviour of wood surfaces weighted by blocks of different geometries and weights could be explained by deformation of the surfaces resulting in a load dependant cohesive term. The difference between values of Young's modulus for sandstone and wood (perpendicular to grain) although difficult to estimate at such low loads is therefore, the most likely explanation for the same relationships not being seen for rock. Medium strength sandstone $E = 1.5 \times 10^6$ p.s.i., Deere, (1968), Scots Pine $E = 4 \times 10^4$ p.s.i., B.R.E. (1974). Deformation is likely to be much less important in the shear resistance of rock sliders.

The results of the experiment to determine degree of wear, using block M4 attached to the worn slider are presented in figures 5.28 and 5.29.

In figure 5.28 the internal angle of the block used for the first 160 cm of sliding is plotted against the angle of sliding for block M4. In figure 5.29 the mass of the original block is plotted against the angle of sliding for block M4. Figure 5.28 illustrates that the sliders that had been attached to squat blocks, when attached to M4, slid at angles close to the angle of sliding for a fresh slider attached to M4. (Appendix 5, figure A5.22). This angle decreased generally with internal

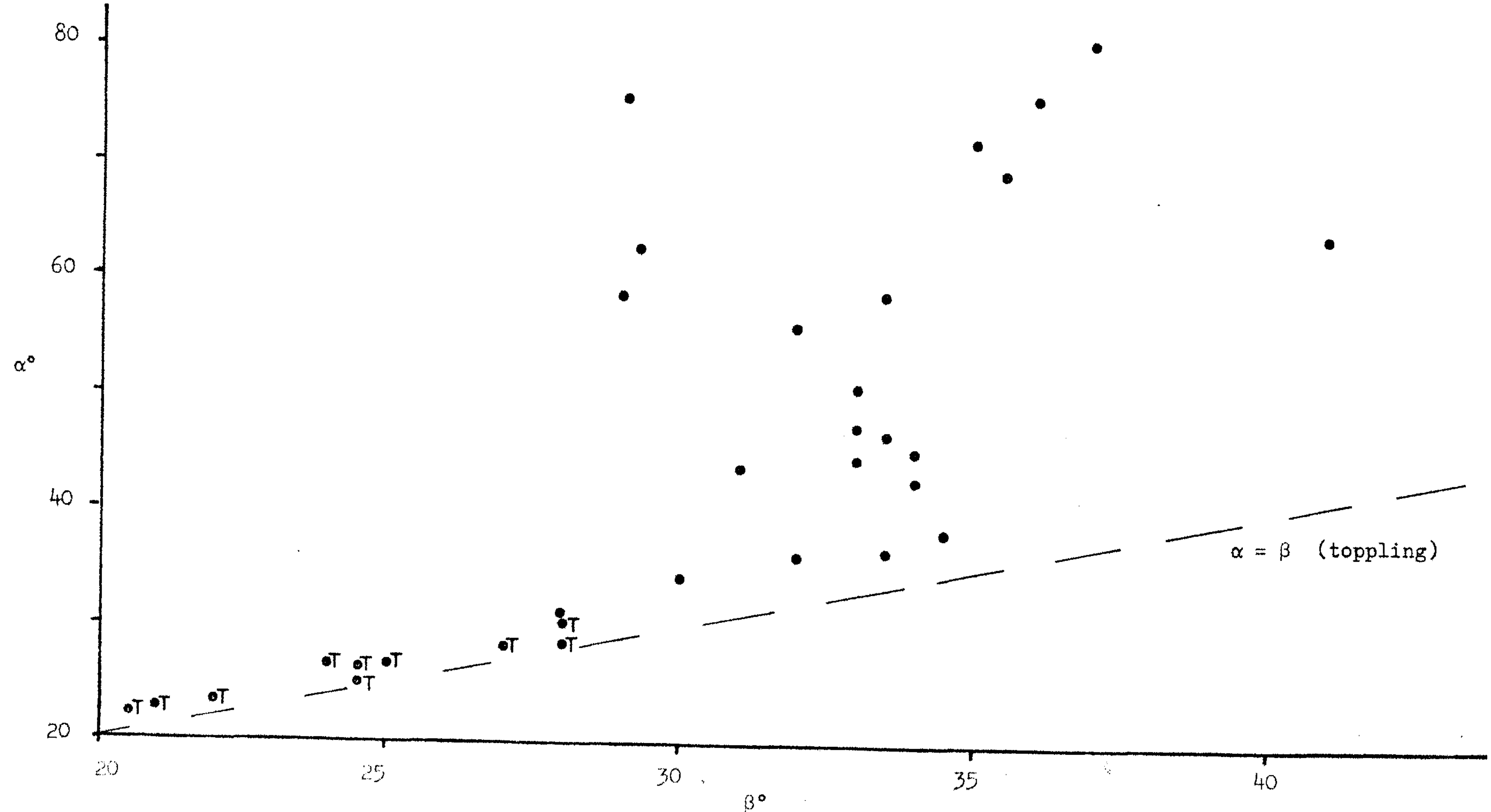

Figure 5.27 Internal angle α° versus angle of sliding β°. Darleydale Sandstone - Position 1

Displacement 0 cm

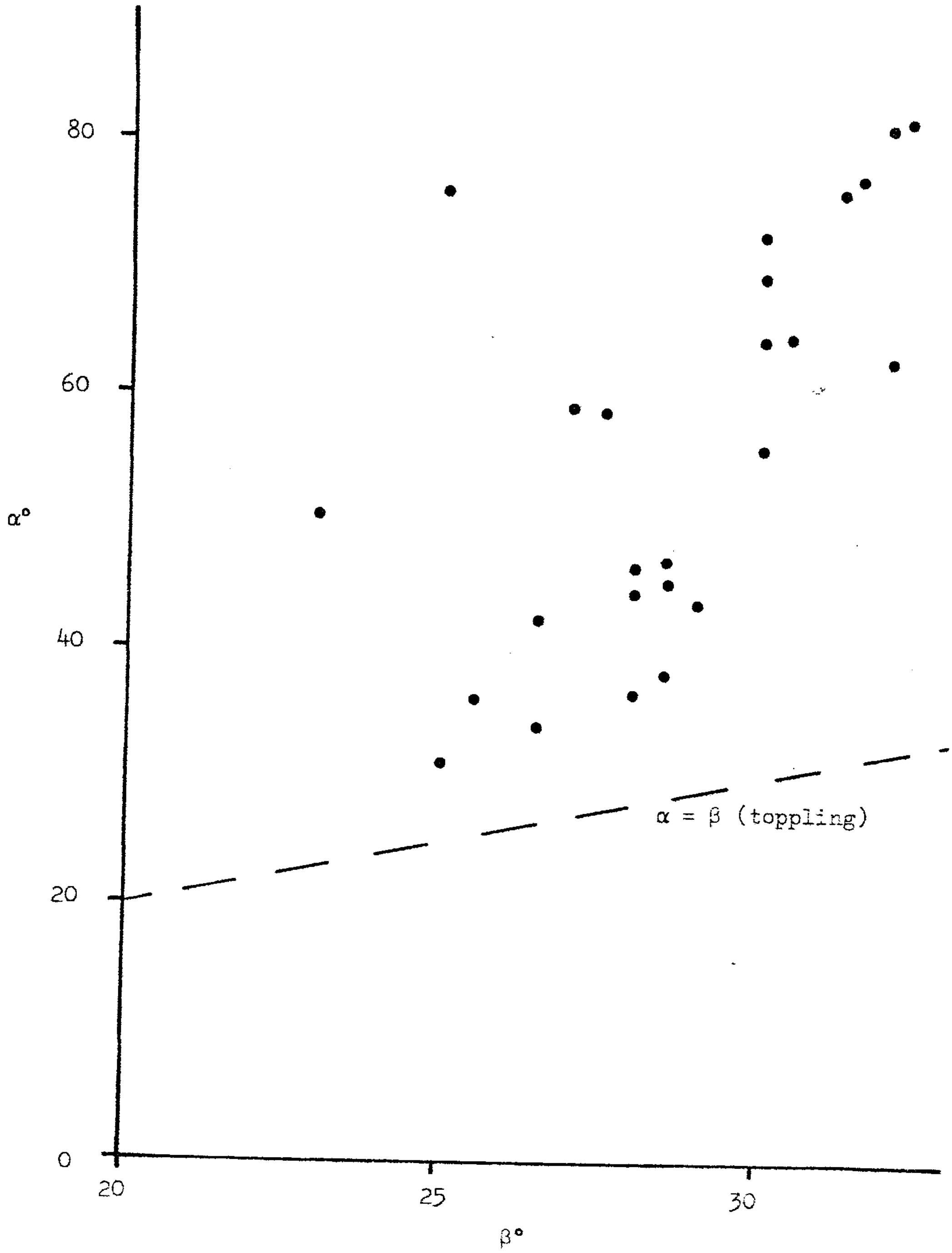

Figure 5.28 Angle of sliding, β, for block M4 on slider already worn by 160 cm sliding attached to block of internal angle α.

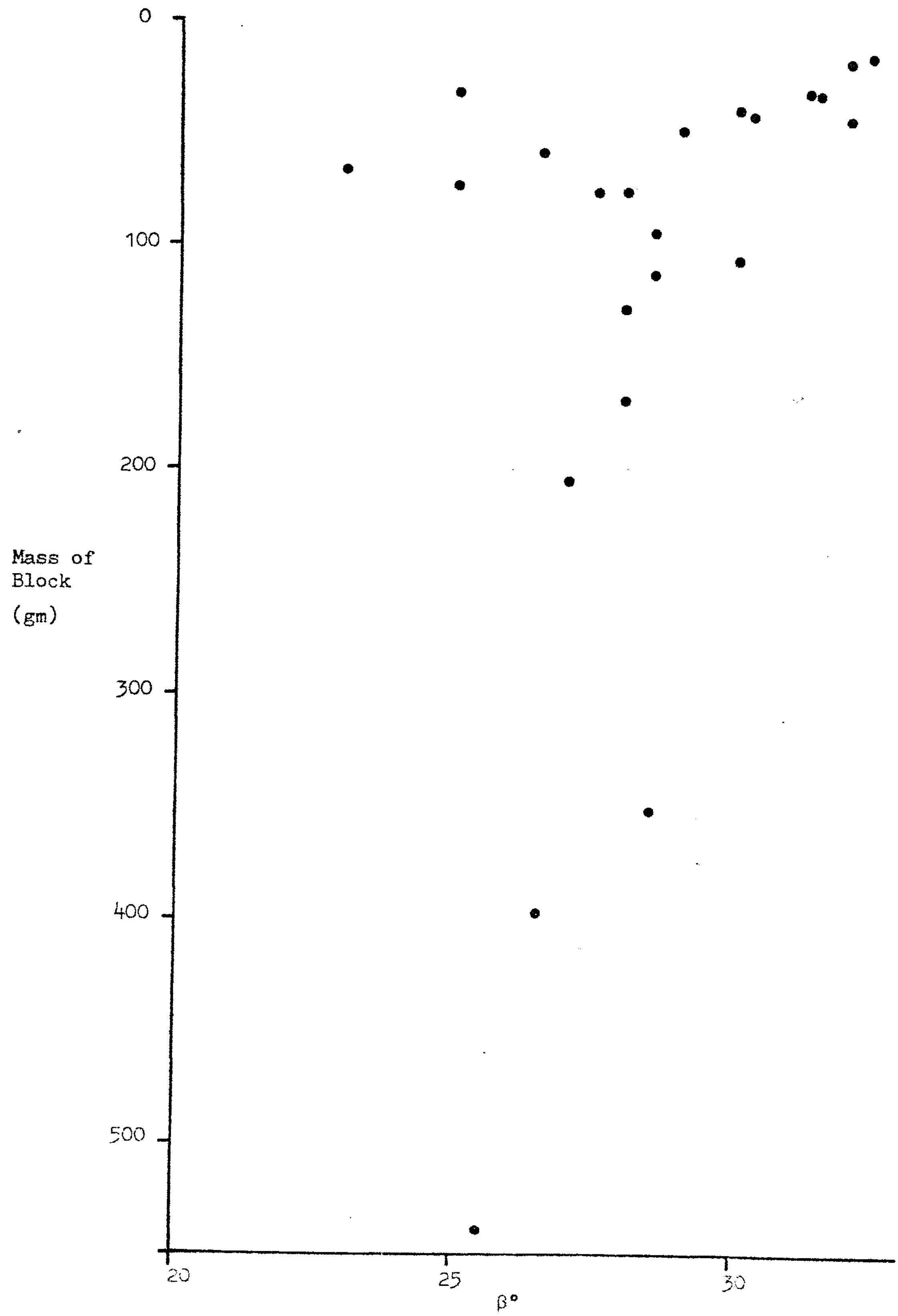

Figure 5.29 Angle of sliding, β, for slider attached to block M4 after 160 cm sliding beneath block of known mass.

angle of the original block used. Figure 5.29 shows no such relationship between the mass of the original block and angle of sliding for M4.

Clearly blocks with basal stress distribution such that wear occurred chiefly at the leading edge show lower angles of sliding for block M4. Blocks where wear had occurred over a wider area than the contact area of M4 at the same angle of inclination, showed relatively little wear at the leading edge and hence presented relatively fresh surfaces for sliding.

Graphs of shear load components versus normal load components for sliding blocks in position 1 are given for data at 0 cm, 32 cm and 160 cm displacement respectively in figures 5.30, 5.31 and 5.32. The data given clearly defines angles of sliding of 33°, 30° and 27° for these three stages. The peak value obtained (33°) agrees well with data obtained by other workers using higher loads and more conventional direct shear apparatus for saw cut and sand blasted surfaces of Darleydale Sandstone, (figure 5.33), Ross-Brown and Walton (1975).

For comparison of figure 5.30 (shear load versus normal load), with figure 5.33 (shear stress versus normal stress), the heaviest block for which results are plotted in figure 5.30 was block M4. When resting on a horizontal plane the average stress over the base of this block is 3,462 N/M^2. When the block is inclined at 32° the peak normal stress (σ_n) at the leading edge is 33,265 N/M^2, peak shear stress (τ) is 20,786 N/M^2.

A problem arises in trying to explain in physical terms the results given in figures 5.30 to 5.32. Clearly the angle of sliding decreases with displacement

so that at 0 cm $\frac{S}{N} = \tan \beta = \tan 33°$