When the residual strengths are plotted against the applied normal stress, far less scatter is noted (Figure 2.2.3.5). A curve fitting program gave shear parameters of C_{jr} = 0,0067 MPa and $\phi_{jr} = 22^0$ when asked to fit a straight line to the points shown below.

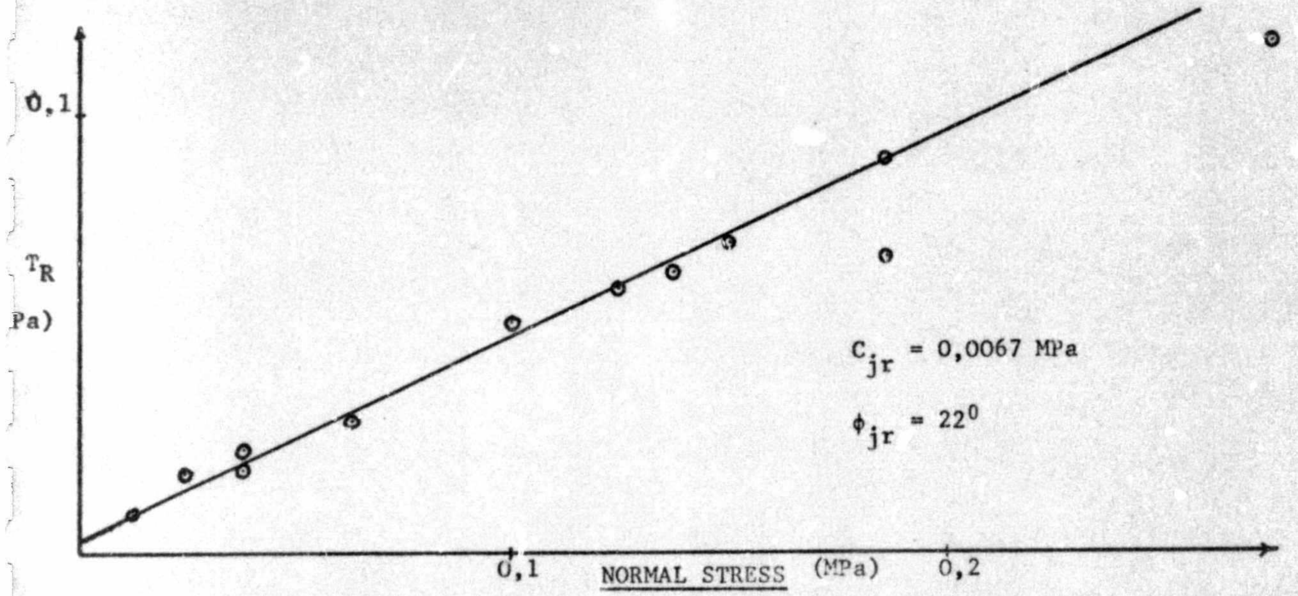


FIGURE 2.2.3.5 RESIDUAL STRENGTH vs APLLIED NORMAL STRESS

At the completion of the tests, the apparatus was dismantled and the two halves could be separated. If one accepts the idea, mentioned above, of the asperities having been sheared; one would expect to find, on the joint surfaces, a powder, or grains of sheared off asperities. This was, however, not found.

2.2.4 Shear Box Tests on the intact Material

The object of these tests was to find the shear strength of the intact material being used in the model tests.

The tests were carried out on 4 inch (101,6 mm) cubes of the plaster of paris at an age of one day and after the cubes had been treated in hot water.

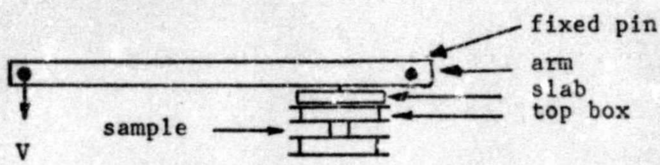


FIGURE 2.2.4.1 DIAGRAM OF SHEAR BOX

ARM	Reaction	=	2,68kN
SLAB	Weight	=	1,04kN
BOX	Weight	=	1,80kN
	Total	=	5,52kN

The apparatus was such (Figure 2.2.4.1) that the minimum vertical loading on

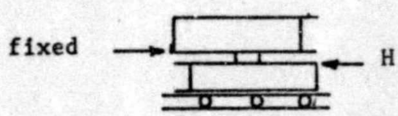


FIGURE 2.2.4.2

HORIZONTAL LOAD, H, APPLIED TO MOVING, LOWER BOX

the sample was 5,52kN. By applying a vertical loading, V, a wide range of normal stresses was obtainable on the sample. A horizontal load, H (Figure 2.2.4.2), was then applied to the lower box by means of a jack. The load was transmitted through the sample into the upper or fixed box. The lower box was on rollers and its deflection at regular load intervals was recorded, sometimes up to peak load, sometimes till residual load. The

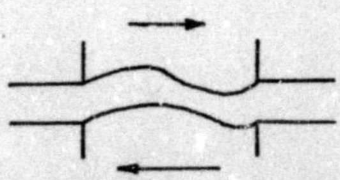


FIGURE 2.2.4.3

TYPICAL FAILURE SURFACE SHAPES

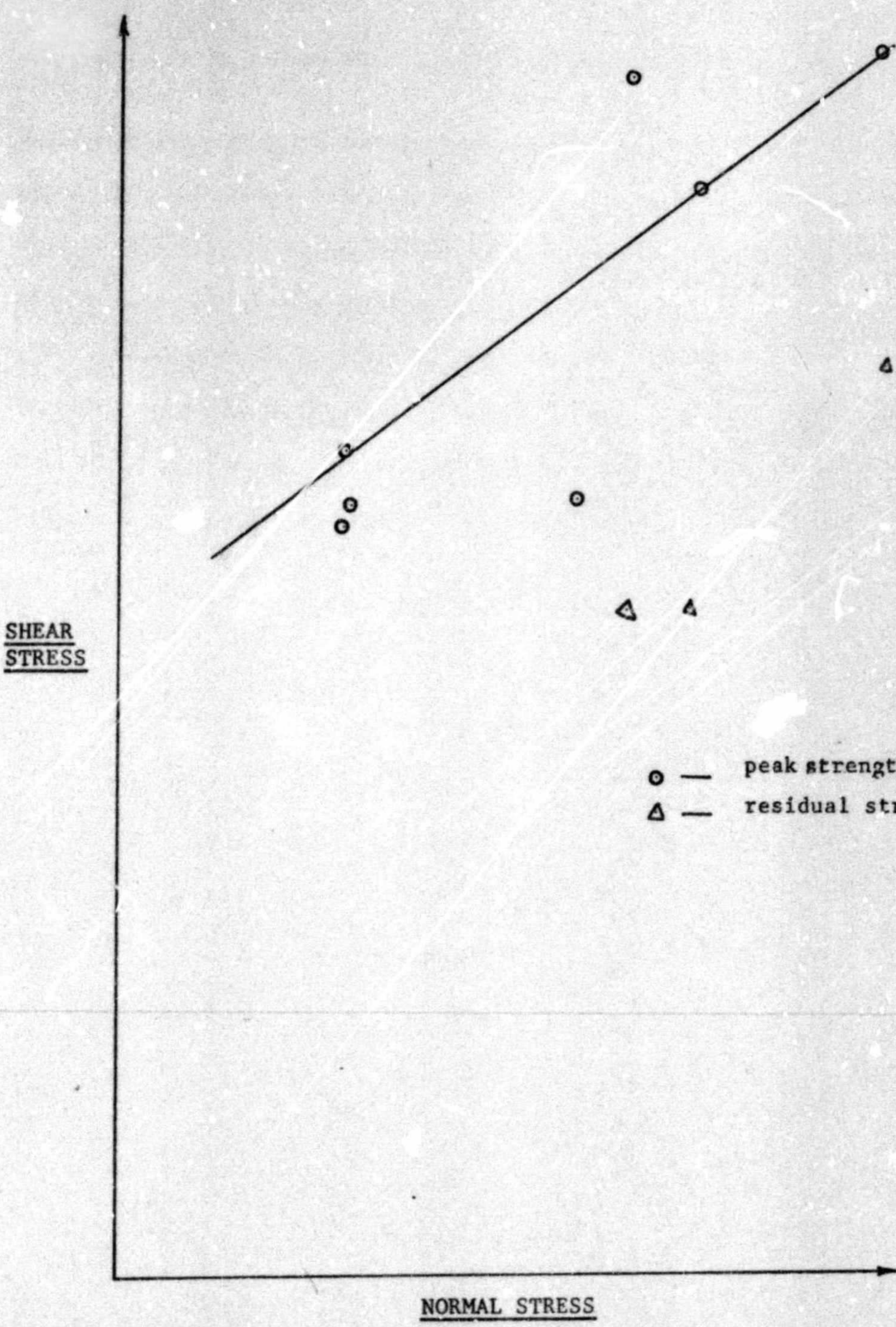


FIGURE 2.2.4.4 SHEAR STRESS vs NORMAL STRESS FOR THE INTACT MATERIAL

apparatus was then dismantled and the failure surfaces inspected.

The failure surfaces tended not to be plane surfaces, but rather of the shape shown in Figure 2.2.4.3. In the middle section there was sometimes very obvious evidence of tension plucking, whereas the two end sections always showed striations. The results of these tests have been plotted on a shear stress vs normal stress graph (Figure 2.2.4.4) and it can be seen that for reasonable values of the shear parameters to be obtained, more tests will have to be conducted. The straight line, fitted to these points by the method of least squares gives C_m = 1,4 MPa and ϕ_m = 41°.

2.3 The Test Procedure

The main tests for this thesis were carried out on 12" x 9" x 2" blocks of plaster of paris. A method of modelling jointed rock was devised.

Plaster of paris was cast into a 2 inch wide mould, onto a flat perspex surface and to the length required (Figure 2.3.1)

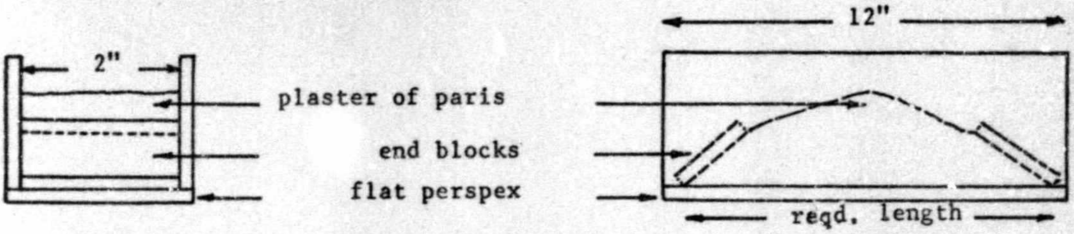


FIGURE 2.3.1 2" WIDE MOULD WITH FLAT PERSPEX BOTTOM

This was then left overnight. The next day, the plaster of paris was taken out of the mould and a thin film of vaseline was spread onto its flat surface. One or more similar pieces of plaster of paris were then fixed into a bigger (12" x 9" x 2") mould, which was 2 inches deep, in the required position(s) (Figure 2.3.2). Plaster of paris was then poured into the big mould, around the pieces fixed in position, until it filled the mould.

The next day, the hardened 12" x 9" x 2" block of plaster of paris was taken

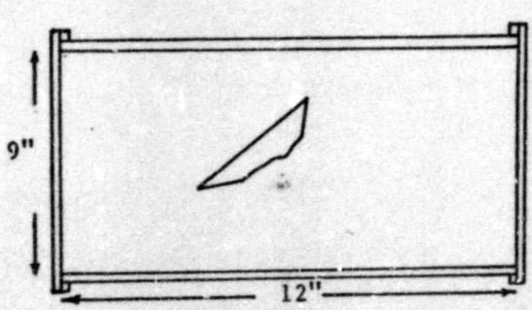


FIGURE 2.3.2 EXAMPLE OF PIECE OF PLASTER OF PARIS FIXED INTO BIG MOULD

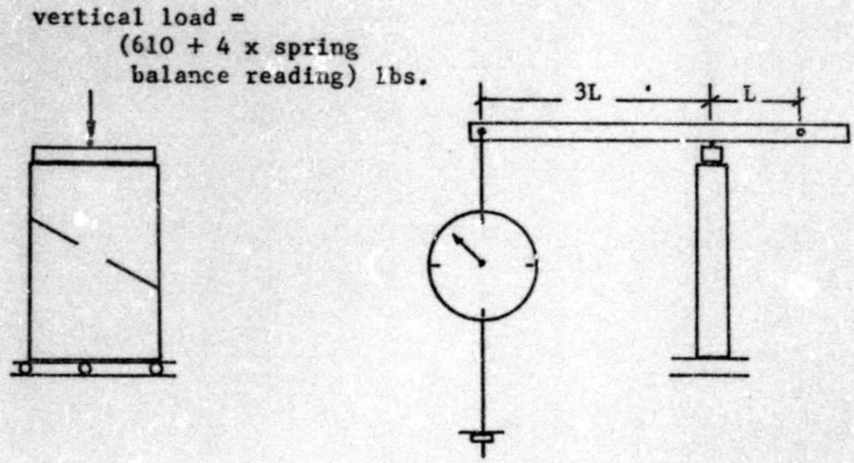


FIGURE 2.3.3 DIAGRAM OF APPARATUS

out of its mould and put into water which was brought to the boil. It was left in the hot water for approximately 40 minutes. When the plaster of paris block had cooled, it could be tested. It was taken to the testing apparatus (Figure 2.3.3) where it was placed on a tray which could move on rollers, thus removing nearly all external restriction on relative horizontal movement between the top and bottom surfaces of the test specimen. A rectangular steel block was placed on top of the plaster of paris which was then loaded in compression. A large structural steel arm, which gave a reaction of 603 lbs (2 717 newtons) was first lowered gently onto the plaster of paris sample. The end of the arm was then connected to a spring balance which could be jacked to apply a load of up to 4 000 lbs (17 818 newtons) at the end of the arm. The jack was operated by means of an oil pump and a load was slowly applied until failure occurred. The ultimate load was recorded and the failure surface and mode of failure were studied.

2.4 Joint Configurations Tested

For this thesis over 70 12" x 9" x 2" jointed plaster of paris blocks were tested with the object of determining their modes of failure. These blocks were an attempt at a demonstration model of jointed rock and in the tests it was hoped that the 2-dimensional behaviour of jointed rock under stress would be modelled.

For the purposes of these tests, joint configurations involving one or two joint directions were classified into four classes, i.e. (see Figure 2.4.1)

1. successive joints all in one plane,
2. parallel joints in more than one plane,
3. joints in 2 directions (α and ψ) in which only a tension fracture is required for stepping down from one α-joint to the next, and
4. joints in 2 directions (α and ψ) in which some form of shearing is required in addition to a tension fracture for stepping down from one

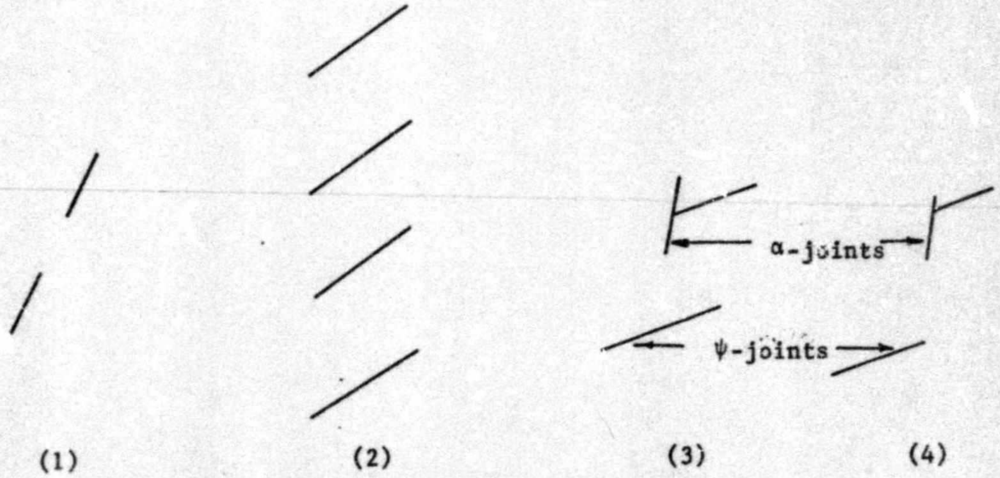


FIGURE 2.4.1 THE 4 JOINT CONFIGURATION CLASSES

α-joint to the next.

Each class and its parameters will now be briefly introduced and discussed.

2.4.1 Class 1

A Class 1 configuration has parallel joints in one plane.

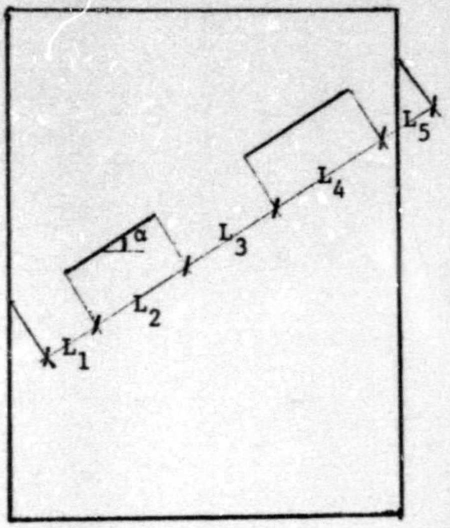


FIGURE 2.4.1.1

CLASS 1 MASTER DRAWING SHOWING PARAMETERS TO BE VARIED

The continuity of jointing is defined as: $k = \dfrac{L_2 + L_4}{L_1 + L_2 + L_3 + L_4 + L_5}$

In these tests α, L_1, L_2, L_3, L_4, L_5 and hence k are all varied.

2.4.2 Class 2

A Class 2 configuration has parallel joints in more than one plane.

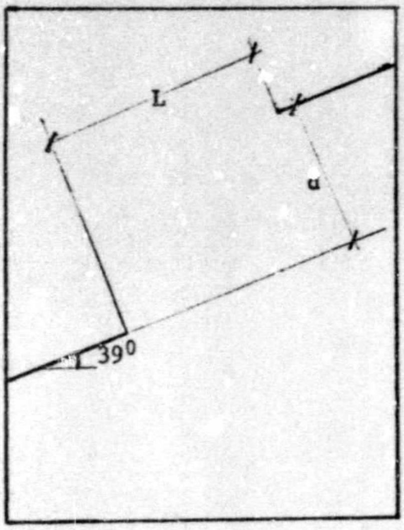


FIGURE 2.4.2.1

CLASS 2 MASTER DRAWING SHOWING PARAMETERS TO BE VARIED.

In these tests, both L and d are varied.

Note: In the calculations, the total length of joint has been called L_{ja}.

2.4.3 Class 3

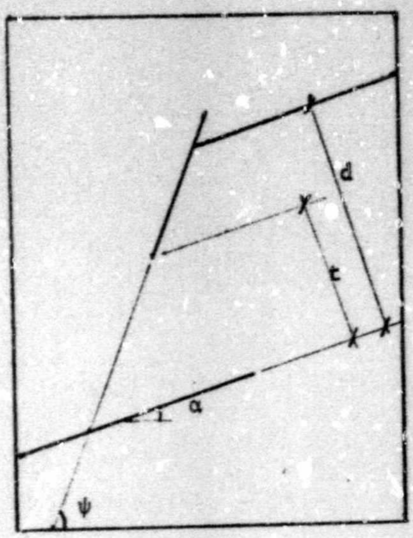


FIGURE 2.4.3.1

MASTER DRAWING SHOWING SALIENT PARAMETERS.

A Class 3 configuration has joints in two directions (given by the angles α and ψ measured from the horizontal) and a tension fracture only is required through the intact material for stepping down from one α-joint to the next.

Only 2 Class 3 configurations were tested because of the well established failure mode.

2.4.4 Class 4

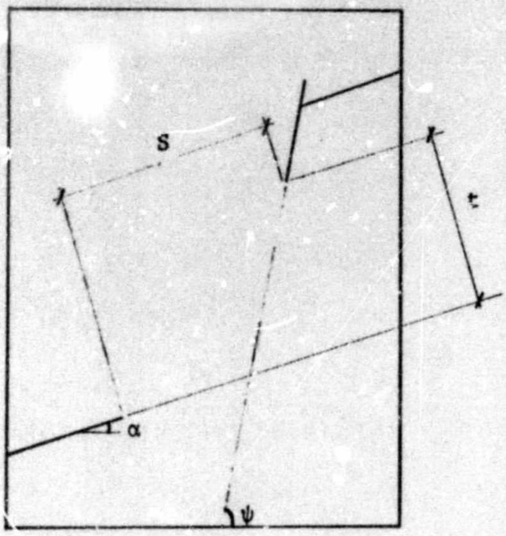


FIGURE 2.4.4.1

MASTER DRAWING SHOWING SALIENT PARAMETERS

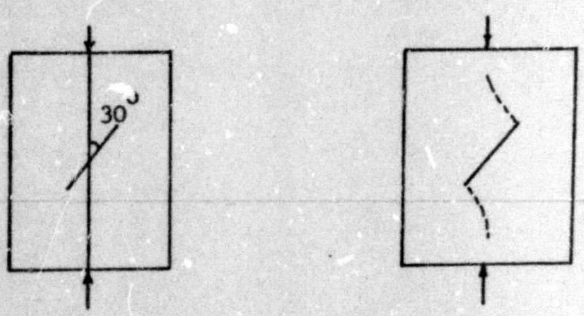
A Class 4 configuration has joints in 2 different directions (given by the angles α and ψ, measured from the horizontal) and a shearing action is required in the intact material for stepping down from one α-joint to the next.

In these tests, all of α, ψ, S and t are varied.

2.5 Results

As a different type of behaviour, or mode of failure, was expected from each joint configuration class, the results of the tests will be dealt with in their different classes. Before dealing with the classes, the result of a preliminary test will be given.

A test was conducted to try to ascertain whether the joints being made, in the fashion described, were a good representation of joints in rock. A 12" x 9" x 2" block was cast with an 84 mm long joint made into it at 30^{o} to the direction of compression loading (Figure 2.5.1 (a)). After being in hot water, the block was subjected to uniaxial compression, in response to which the block started to crack near the ends of the joint. The cracks grew, curved, approached the direction of compression and finally stopped after travelling between one and two joint lengths (Figure 2.5.1 (b)). As



(a) (b)

FIGURE 2.5.1

this result was exactly what was expected from work conducted by Brace and Bombolakis (1963) in which cracks grew unaided under compression, sending out branch fractures from their ends, it was felt that a reasonable model had been achieved.

As already mentioned, the results of the rest of the tests will be given in their respective classes. Each class will have its results tabulated and summarized. In an appendix at the back of this thesis can be found photographs, in numerical order, of most of the failed sample blocks. The symbol, W, will represent the failure load of the sample given in kilonewtons.

2.5.1 Class 1 Results

TABLE 2.1 FAILURE DETAILS OF THE CLASS 1 SAMPLES TESTED

SAMPLE NO.	$\alpha(^o)$	k	W (kN)	FAILURE MECHANISMS OBSERVED				
				BC	TF	JS	S1	S
6	30	0,64	50,0	2	2	2	2	1
64	30	0,8	46,7	2	2	2	2	1
66	30	0,8	45,6	2	2	2	2	
70	30	0,8	41,6			2	2	
1	38	0,71	40,9	2	2	2	2	1
63	40	0,8	25,4	1		2	2	
67	40	0,8	19,2	1		2	2	
69	40	0,8	19,5	2	2	2	2	
65	49½	0,8	14,0			2	2	
68	49½	0,8	18,2			2	2	
62	50	0,8	18,8	1		2	2	1
71	50	0,8	?			2	2	

BC stands for branch cracks

TF stands for tension fracture (axial cleavage)

JS stands for shear along joint surfaces

S1 stands for shear through intact material

S stands for spalling of material from the sides of the sample block

1 indicates that this mode had a minor influence on the failure

2 indicates a major participation in the failure

The results of the Class 1 tests are tabulated in Table 2.1. Provided that the "weakening effect" (determined by α and k) of the joints was great enough, the "expected" failure mechanisms in these tests were shear along the joints and shear through the intact material between the joints. As can be seen from

2.5.1 Class 1 Results

TABLE 2.1 FAILURE DETAILS OF THE CLASS 1 SAMPLES TESTED

SAMPLE NO.	α(°)	k	W (kN)	FAILURE MECHANISMS OBSERVED				
				BC	TF	JS	SI	S
6	30	0,64	50,0	2	2	2	2	1
64	30	0,8	46,7	2	2	2	2	1
66	30	0,8	45,6	2	2	2	2	
70	30	0,8	41,6			2	2	
1	38	0,71	40,9	2	2	2	2	
63	40	0,8	25,4	1		2	2	
67	40	0,8	19,2	1		2	2	
69	40	0,8	19,5	2	2	2	2	
65	49½	0,8	14,0			2	2	
68	49½	0,8	18,2			2	2	
62	50	0,8	18,8	1		2	2	1
71	50	0,8	?			2	2	

BC stands for branch cracks

TF stands for tension fracture (axial cleavage)

JS stands for shear along joint surfaces

SI stands for shear through intact material

S stands for spalling of material from the sides of the sample block

1 indicates that this mode had a minor influence on the failure

2 indicates a major participation in the failure

The results of the Class 1 tests are tabulated in Table 2.1. Provided that the "weakening effect" (determined by α and k) of the joints was great enough, the "expected" failure mechanisms in these tests were shear along the joints and shear through the intact material between the joints. As can be seen from the table and the photographs (particularly Sample No. 70), these mechanisms always occurred; however, as the weakening effect of the joints decreased (i.e. low α and low k) these mechanisms tended to occur in conjunction with others.

Branch cracks grew from the ends of the joints, as already described. These branch cracks often led to almost vertical axial cleavage or tension fracture through the plaster of paris (see photographs of Sample Nos. 1, 6 and 69). The upper part of the tension fracture in Sample No. 69 is a good example of a branch crack shape. The other failure mechanism which occurred was the spalling of plaster of paris off the sides of the blocks, as is observed in nearly all compression tests on concrete. This mechanism occurs because the tests are three-dimensional, and when discussing two-dimensional tests it can accurately be described as as "end effect". The influence of spalling on the failure of a very long slope would be negligible.

These three "secondary" failure mechanisms are almost non-existant at $\alpha = 50^{o}$ and $k = 0,8$, whereas they are very common at $\alpha = 30^{o}$ even at $k = 0,8$.

The failure load values were reasonably consistent for each different configuration and showed definite tendency to

i) increase as k decreased, and to

ii) decrease as α increased

as expected.

2.5.2 Class 2 Results

The results of the Class 2 samples tested are given in Tables 2.2 (a) and 2.2 (b).

The Class 2 results can be split up into those with a negative or zero value of L and those with a positive value of L. Those with a negative or zero value of L need only a tension fracture through the intact material between the joints in addition to shearing along the joint surface for failure of the sample. In all but one case (No. 35) this has occurred (see photographs (e.g. Nos. 2 and 9) and Tables 2.2 (a) and (b)). A feature here is the number of times that two sub-parallel tension fractures have occurred through the intact material leaving a block of material between the two parallel joints. (See Samples 14 and 25). This probably results from a field of high tensile stress. One might expect straight tension fractures, at right angles to the joint surfaces giving a failure surface of minimum area. However, these are noticeably absent, and if one looks at the shapes of the tension fracture surfaces in Sample Nos. 12 and 24, it becomes clear that, at least, some of these fractures start as branch cracks, particularly as most of the fracture surfaces start at joint ends.

Those samples with positive values of L require, in addition to shear along joint surfaces and tensile fracture, a shearing failure through the intact material between the joints, for failure of the sample. This, of course (with the other parameters remaining constant), requires higher stresses. It is these higher stresses which give other failure mechanisms (e.g. branch cracks and spalling) a chance to occur (e.g. Nos. 21 and 22); i.e. the "weakening effect" (which now depends on the continuity and d, since α is a constant) is not nearly as great. (Note also that for d = 25 mm only one sample exhibited branch cracking).

TABLE 2.2 (a) FAILURE DETAILS OF CLASS 2 SAMPLES WITH d = 51 mm

SAMPLE NO.	L (mm)	W (kN)	FAILURE MECHANISMS OBSERVED					
			JS	T1	S1	BC	TF	S
2	-20	>2,7	2	2				
4	-11	13,0	2	2				
30	-20	9,9	2	2				
31	-20	7,9	2	2				
32	-20	24,2	2	2				
9	0	20,6	2	2				
12	0	>2,7	2	2				
14	0	?	2	2				
24	0	29,8	2	2				
25	0	11,1	2	2				
26	0	18,2	2	2				
10	81	15,6	2	2	2			
15	81	38,0	2	2	2			
16	81	19,3	2	2	2			
27	81	15,0	2	2	2			
28	81	37,6	2	2	2	2	2	
29	81	10,9	2	2	2			
11	158	30,9	2	2	2	?	2	
17	158	35,8	2	2	2			
18	158	36,6	2	2	2	1		
19	158	34,3	2	2	2	1		1
21	158	52,4	2	2	2	2	2	
22	158	34,3	2	2	2	2	2	1

For notation see Table 2.2 (b)

TABLE 2.2 (b) FAILURE DETAILS OF CLASS 2 SAMPLES WITH d = 25 mm

SAMPLE NO.	L (mm)	W (kN)	FAILURE MECHANISMS OBSERVED			
			JS	T1	S1	BC
33	-41	10,0	2	2		
34	-41	25,6	2	2		
35	-41	23,8	2	2	2	1
39	0	2,7	2	2		
40	0	2,7	2	2		
43	0	13,6	2	2		
44	36	17,9	2	2	2	
45	36	61,9	2	2	2	
46	36	14,0	2	2	2	
47	36	49,4	2	2	2	
48	36	13,6	2	2	2	
36	74	24,2	2	2	2	
37	74	24,3	2	2	2	
38	74	28,0	2	2	2	
49	74	52,4	2	2	2	

JS stands for shear along joint surfaces

T1 stands for tension fracture linking two joints through originally intact material

S1 stands for shear through originally intact material

BC stands for branch cracks

TF stands for tension fracture definitely related to a branch crack

S stands for spalling of material off the sides of the block

2 indicates a major participation in the failure

1 indicates a minor influence on the failure

(This [illegible] also applies to Table 2.2 (a) overleaf)

Author Goodman Hubert John
Name of thesis The Nature Of Failure Through The Intact Materials In The Step Joint Mechanism For Rock Slopes. 1973

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