Basic Friction Angles of Carbonate Rocks from Kananaskis Country

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ABSTRACT

Basic friction angles of the Paleozoic carbonate rocks of Kananaskis Country, west of Calgary, Canada were determined on a tilting table to range from 21.5° to 41.3°. The basic friction angles of carbonate rocks with impurity contents under 10% increase with calcite content and grain size. Clay minerals and reduce basic friction angles in carbonate rocks with impurity contents over 10%. Sliding angles from repeated tests decrease with displacements for dolostones but not for limestones. The friction angles of highly polished surfaces are 7.5 to 7.9° for dolostones and 11.8 to 13.0° for limestones, a difference attributed to the frictional properties of the minerals.

RESUME

On a mesuré les angles de frottement de base des roches Paléozoiques carbonatées en Kananaskis Country, a l'ouest de Calgary, Canada par un tableau inclinant dans l'intervalle de 21.5 a 41.3°. Les angles de frottement de base des roches carbonatées qui ont moins d'un dixieme des impuretés, augmentent en correlation avec la teneur de calcite et les dimensions des grains. Les minéraux argileux en lubrifiant les surfaces glissants, reduisent les angles de frottement de base des roches carbonatées qui ont plus d'une dixeme des impuretes. En faisant des epreuves successives, les angles de glissement des dolomies diminuent. Ce n'est pas le cas pour les calcaires. Les angles de frottement des surfaces extrêmement lisses sont 7.5 - 7.9° en cas des dolomies et 11.8 - 13.0° en cas des calcaires. On attribut cette différence aux caracteristiques des surfaces minéraux.

INTRODUCTION

Frictional properties along discontinuities within rock masses control the resistance of natural rock slopes to sliding. So estimates of friction angles along discontinuities are necessary to evaluate stabilities of rock slopes. Patton (1966) demonstrated that shearing resistance along discontinuities consisted of two components, a frictional resistance between two sawn surfaces of rock represented by ϕ_b, the basic friction angle, and a topographic component represented by i, the roughness angle along discontinuities. Cruden (1985) recommended that the basic friction angle can be used as a conservative estimate of the friction angle along a discontinuity in a stability analyses except when the rock had been softened and altered or when the discontinuity had been polished by displacement.

Coulson (1970) recommended that the basic friction angle be measured on surfaces rough-sawn and then lapped with #80 grit paper. Coulson (1972) gave several profiles of prepared rock surfaces with different roughnesses. He observed that the surface roughness of some limestones and sandstones were controlled by their porosity and by individual grains if the grain size of the lapping compound was appreciably less than the grain size of the rock. Bruce (1978) noted that the basic friction angle is the sum of the friction angle of polished mineral surfaces, ϕ_m, and small scale roughness due to sandblasting. Eaton (1986) measured basic friction angles of carbonates and quartzites from Kananaskis Country using a tilting table described by Bruce, Cruden and Eaton (1987). Eaton (1986, pp. 117-118) noted that the lower bound of the basic friction angles of dolostones is less than that of limestones. So basic friction angles of carbonates are dependent on at least two factors, mineral composition and the grain sizes of rocks.

In a recent survey of natural slopes in 884 km^2 of Kananaskis Country, Alberta (Cruden and Eaton, 1987), the basic friction angles of the slope forming rocks were found to range from 25° to 40°. The stratigraphic units in which the slopes were studied include the Devonian Fairholme Group, the Devonian Palliser Formation, the Mississippian Banff Formation, the Mississippian Rundle Group, the Permo-Pennsylvanian Rocky Mountain Group and the Triassic Sulphur Mountain Formation (Bielenstein *et al.*, 1971). The large range of basic friction angles in these rocks prompted a study of factors controlling friction in the carbonates in the succession. In a study of overdip slopes (Cruden, Eaton and Hu, 1988), 30 crystalline carbonate samples were taken from the Fairholme Group, the Palliser Formation, the Banff Formation and the Rundle Group to determine basic friction angles and to study the variation of basic friction angles of carbonate rocks.

Three quarters of the total land area of the Earth is underlain directly by sedimentary rocks and carbonates form 15% of these sedimentary rocks (Sweeting, 1972, p.6). The results of this research on the basic friction angles of carbonates can be applied to these other carbonate rocks with the possible exception of comparatively soft chalks or detrital carbonate rocks.

SAMPLE PREPARATION AND TESTING PROCEDURE

The rock samples were cut by rock saws to 5 cm square tablets, 1.5 to 2.5 cm thick and then lapped with #80 grit using water to distribute grit evenly on the lapping table for 90 minutes. The samples were then cleaned with an air hose at a pressure of 965 KPa.

A tilting table constructed by Eaton (1986) at the University of Alberta was used to determine basic friction angles of the samples. A rigid frame supports a hinged table and electric motor assembly. The drive assembly rotates a drum which has a wire cable attached to the hinged table which is equipped with brackets to hold samples up to 15 cm on a side. The bottom sample or plate is mounted in the brackets and the top sample or slider is placed on top of it. A linear voltage displacement transducer and a rotary voltage displacement transducer both connected to a X-Y plotter record the movement of the slider and the rotation of the table.

Each pair of samples on the tilting table was tilted until the slider slid over the bottom sample. Tests were conducted at the rate of 8° per minute. The inclination of the table at which the displacement between the slider and the plate was over 2 cm was recorded and its mean value from 5 to 8 successive tests was used as an estimate of the basic friction angle.

Mineral compositions of carbonate samples were determined by chemical analyses. The samples were decomposed with hydrochloric acid following the method of Hillebrand *et al.* (1953). $CaCO_3$ and $CaMg(CO_3)_2$ contents were determined by atomic absorption and the insoluble materials were examined under a binocular microscope. The dolomite composition, $CaMg(CO_3)_2$, assumes no ionic substitutions in the lattice of dolomite crystals present.

The percentages of grains larger than 0.06 mm, the boundary between fine grained limestones and calcarenites in the engineering classification of carbonates of Fookes and Higginbottom (1975), were estimated using a binocular microscope and a comparison chart for visual percentage estimation of grains (Terry and Chilingar, 1955). Because the percentages of the grains were estimated from flat surfaces, the percentages of grains larger than 0.06 mm have been underestimated due to the cut effect.

Four samples, two with calcite contents over 97% and two with dolomite contents over 95% were selected to determine the friction angles of mineral surfaces of calcite and dolomite. Plates were relapped with #1000 grit and then polished with tin oxide on a polishing table. The sliders were sandblasted with #80 grit. The tilting tests were conducted under dry conditions.

The uniaxial compressive strengths of the samples were estimated from indentation tests (Mining Research and Development Establishment, 1977) and the unit weights of the samples were also determined in the standard way.

TEST RESULTS

Basic friction angles, listed in Tables 1 and 2, show that when the insoluble material (impurity) content of the rock is larger than 10%, the basic friction angle is less than 32° and when the impurity content is less than 10%, the basic friction angle ranges from 21.8° to 41.4°. 10% insolubles by weight separate impure and pure carbonates in the carbonate classification of Leighton and Pendexter (1962).

The unit weights of the samples are between 2.58 g/cm^3 and 2.81 g/cm^3 for all the samples except 8-1 whose 2.21 g/cm^3 is due to comparatively larger porosity. The unit weights of dolostones are larger than those of limestones. The uniaxial compressive strengths of the samples estimated from indentation tests range from 121 MPa to 325 MPa; dolostones are generally stronger than limestones.

22 out of 30 samples were pure carbonates. From the distribution of basic friction angles with respect to the dolomite content and the percentage of grains larger than 0.06 mm (Fig. 1), it can be seen that the basic friction

angle generally increases with the percentages of larger grains and decreases with dolomite contents. A multiple regression analysis of the basic friction angle, ϕ_b, with the dolomite content and the percentage of grains larger than 0.06mm as independent variables gave

$$\phi_b = 32.4-10.2(\text{dolomite content})+7.4(\%\text{coarse grain})$$

The significance level of analysis of variance for the regression analysis is 0.0153 and both variables are significant at the level of 0.05. Only 4 samples out of 22 have the residuals of basic friction angles larger than 6° (Fig. 1). So the value predicted from the regression equation may be a useful estimate of the basic friction angle for pure carbonates to within 6°.

Examinations of the profiles of the surfaces of four samples (Fig. 2) indicate that the surfaces of coarse grained carbonates are rougher than those of fine grained carbonates although all the samples were prepared by the same procedure. The surfaces of the coarse grained limestones are not noticeably rougher than those of the coarse grained dolostones.

The scatter of the basic friction angles, particularly at low dolomite content, indicate that other factors, besides the mineralogy and grain size, may affect the basic friction angle. These may include:

1. Nature of the grains, whether the rock has recrystallised completely so that individual grains are individual crystals or the grains have retained their more rounded, clastic boundaries.

2. Grain size distribution, particularly at the sand grain size.

3. Characteristics of insoluble fractions whether clay, quartz or others, although the impurity content is under 10%.

From the centre line averages and the friction angles for the four highly polished samples given in Table 3, the polishing procedure produces surfaces whose roughnesses are around the micron level. These surfaces have friction angles approaching that of smooth single crystals. For example, the friction angle of calcite determined with smooth, oven-dry buttons of rock shearing over polished plates of rock by Horn and Deere (1962) are between 6.8 and 8.0°. The contact area for the test of Horn and Deere (1962) is much smaller than that for the test done by the authors.

The friction angles of the 4 highly polished samples show that the mineral friction angle of calcite (samples 10-2 and 25-1) is larger than that of dolomite (sample 14-1 and 15-1). The centre line averages of the highly polished samples show the dolostones (14-1, 15-1) are not smoother than limestones (10-2, 25-1). Clearly, the lower friction angles of the dolostones are not due to surface topography differences but reflect mineral properties. The centre line averages also show that the coarse limestones (25-1) and dolostones (14-1) are rougher than the fine limestones (10-2) and dolostones (15-1) respectively although the samples were prepared by the same method.

8 out of 30 samples were impure carbonate samples. The major minerals in insoluble materials are clay minerals and quartz. The relatively low basic friction angles of impure carbonates might be due to clay minerals that can lubricate sliding surfaces.

Bishop's brittleness index (1973) was modified to study the trend of the relationship between the sliding angle, ϕ_i and displacement for the repeated tests of each pair of samples. A modified brittleness index, I_{mb}, taking every reading in the repeated tests into account is defined in Equation 1.

$$I_{mb} = \Sigma[(\phi_{i+1}-\phi_i/\phi_{max}] \quad (1)$$

where ϕ_i and ϕ_{i+1} are the sliding angles of ith and (i+1)th tests in a testing sequence and ϕ_{max} is the maximum sliding angle of the testing sequence.

The modified brittleness indexes for all the samples form Table 4. The modified brittleness indexes for 11 out of 12 sawn dolostone sliding tests are positive, which indicates that the sliding angle decreases with displacement. The modified brittleness indexes are positive for some limestone samples and negative for some others so there is no distinct relationship between the sliding angle and the displacement for limestones.

CONCLUSIONS

Basic friction angles of carbonate rocks are controlled by mineralogy and grain sizes. For pure carbonate rocks, increasing dolomite contents decrease basic friction angles while big grain sizes increase basic friction angles. The basic friction angles vary from 21.5° to 41.4°. For impure carbonate rocks basic friction angles are generally less than 31.5° depending on clay mineral and quartz content. The friction angles generally decrease with displacement for dolostones but there is no relationship between the friction angle and the displacement for limestones.

The low friction angles and brittleness of dolostones suggests careful attention be paid to these rocks in a sequence of carbonates whose stability on slopes is under evaluation.

Table 1. Dolomite contents, percentages of grains larger than 0.06 mm, basic friction angles, unit weights and uniaxial compressive strengths of the pure carbonate samples.

samples	CM	SIZE	ϕ_b	γ	σ_c
1-1	48.1	35	35.4	2.72	227
1-2	53.9	50	33.5	2.71	267
2-1	2.6	15	24.5	2.71	233
7-1	45.6	20	26.8	2.74	198
7-3	14.0	5	38.0	2.69	246
8-1	10.3	5	22.8	2.21	160
8-2	6.3	45	38.1	2.65	211
9-1	16.8	10	32.4	2.70	260
9-2	4.4	50	41.3	2.58	121
10-1	69.4	50	30.6	2.73	165
10-2	1.9	0	28.6	2.67	189
14-1	95.9	95	23.9	2.81	267
15-1	97.9	10	21.5	2.81	207
16-1	22.9	50	33.4	2.71	239
20-1	7.3	20	35.7	2.68	239
25-1	2.3	80	39.4	2.67	202
26-1	64.8	80	34.7	2.75	267
27-1	2.9	80	30.8	2.66	227
30-1	4.4	0	30.3	2.68	253
31-1	16.2	0	34.8	2.69	260
35-1	2.1	70	39.0	2.62	227
43-1	13.4	10	34.3	2.71	260

CM: Percentage dolomite contents.

SIZE: The percentages of the grains larger than 0.06 mm.

ϕ_b: Basic friction angles in degrees.

γ: Unit weights (grams per cubic centimetre).

σ_c: Uniaxial compressive strengths (MPa).

Table 2. Dolomite contents, clay mineral contents, quartz contents, percentages of the grains larger than 0.06 mm, basic friction angles, unit weights and uniaxial compressive strengths of the impure carbonate samples.

samples	CM	CL	QU	SIZE	ϕ_b	γ	σ_c
4-1	2.5	8.2	32.8	10	24.0	2.67	253
7-2	37.6	42.8	2.2	5	30.1	2.78	325
13-1	78.9	18.1	1.0	0	24.1	2.77	276
27-2	27.0	18.2	54.8	5	28.2	2.66	303
28-1	2.3	1.5	27.7	10	29.1	2.67	233
28-2	66.1	25.8	1.4	15	31.5	2.75	260
29-1	11.8	0.7	13.7	10	31.5	2.70	233
42-1	42.0	17.8	2.0	15	34.5	2.70	253

CL: Percentage Clay mineral contents.

QU: Percentage Quartz contents.

Table 3. Centre line averages and friction angles from rock surfaces lapped by #1000 grit and then polished with tin oxide.

samples	centre line average value (micron) cut-off 2.54 mm	0.762 mm	0.254 mm	friction angle (degree)
14-1 c dl	0.27	0.20	0.18	7.9
15-1 f dl	0.25	0.20	0.12	7.5
10-2 f-c ls	0.20	0.19	0.11	13.0
25-1 c ls	0.19	0.16	0.13	11.8

c: coarse grained

f: fine grained

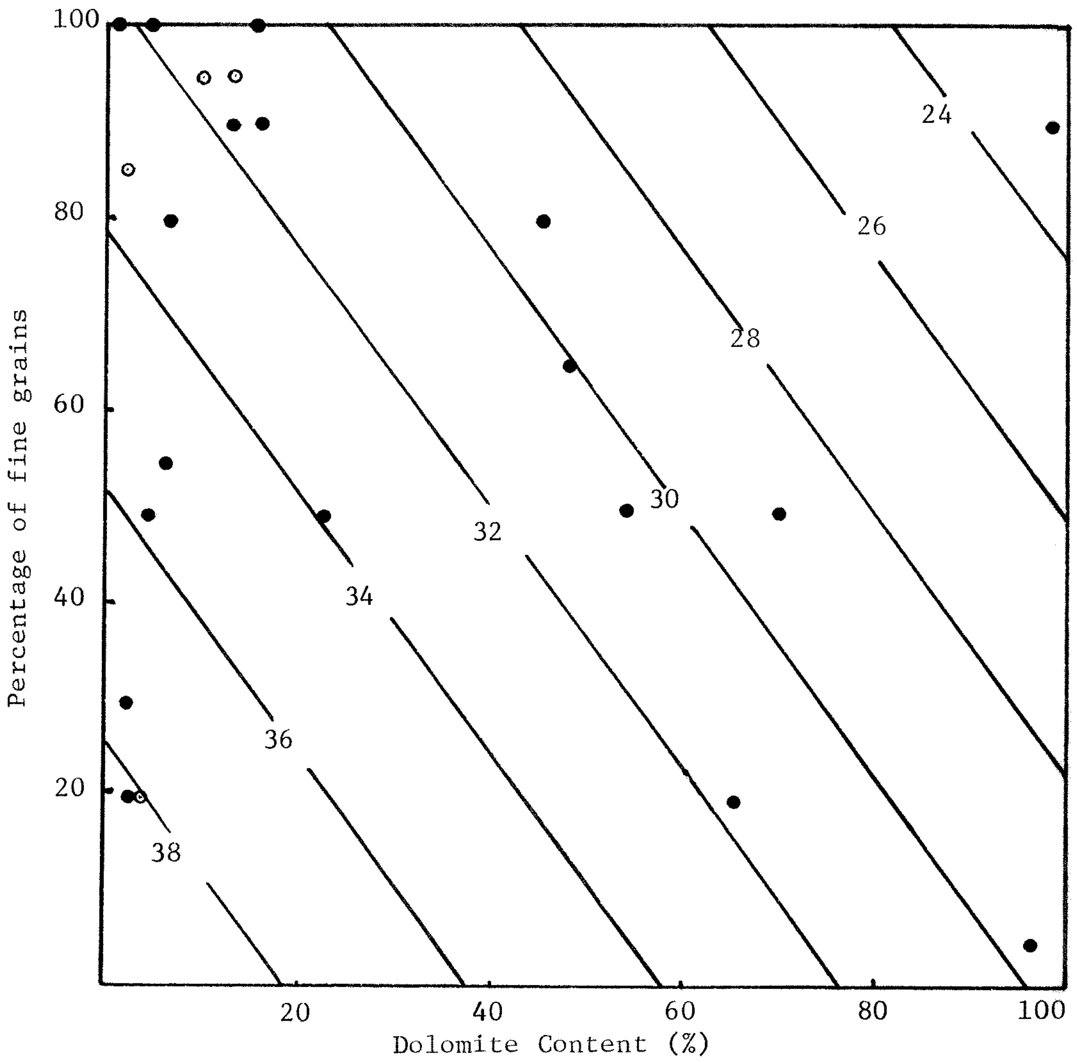
f-c: fine to coarse grained

dl: dolostone

ls: limestone

Table 4. Modified brittleness indexes for the sliding samples.

Sliding Samples	Modified Brittleness Indexes	Lithology	Sliding Samples	Modified Brittleness Indexes	Lithology
1-1-1	0.055	f-c ls	15-1-1	0.039	f dl
1-1-2	-0.043	f-c ls	15-1-1	0.090	f dl
1-1-2	-0.110	f-c ls	16-1-1	0.090	f ls
1-2-1	-0.080	f-c ls	16-1-2	0.072	f ls
1-2-2	0.027	f-c ls	20-1-1	0.144	f-c ls
2-1-1	-0.049	f ls	20-1-2	0.124	f-c ls
2-1-2	-0.063	f ls	25-1-1	0.077	c ls
4-1-1	-0.081	f ls	26-1-1	-0.051	c ls
7-1-1	-0.103	f ls	27-1-1	0.064	f-c ls
7-2-1	0.054	f dl	27-1-2	0.113	f-c ls
7-2-2	0.064	f dl	27-2-1	0.111	f dl
7-3-1	0.018	c ls	27-2-2	0.234	f dl
7-3-2	0.035	c ls	28-1-1	0.281	f ls
8-1-1	-0.079	f ls	28-1-2	0.301	f ls
8-2-1	-0.097	c ls	28-2-1	0.127	f dl
8-2-2	-0.056	c ls	29-1-1	0.194	f-c ls
9-1-1	-0.144	f-c ls	29-1-2	0.252	f-c ls
9-1-2	0.006	f-c ls	30-1-1	0.142	f ls
9-2-1	-0.046	c ls	30-1-2	0.170	f ls
9-2-2	0.026	c ls	31-1-1	0.021	f ls
10-1-1	0.061	f-c ls	31-1-2	0.143	f ls
10-1-2	0.035	f-c ls	35-1-1	0.146	c ls
10-2-1	0.153	f-c ls	35-1-2	0.012	c ls
10-2-2	0.063	f-c ls	42-1-1	0.165	f dl
13-1-1	0.380	f dl	42-1-2	0.039	f dl
13-1-2	-0.123	f dl	43-1-1	0.133	f-c ls
14-1-1	0.085	c dl	43-1-2	0.063	f-c ls



○ Sample which has the residual of the basic friction angle from the regression equation over 6 degree.

● Sample which has the residual of the basic friction angle from the regression equation less than 6 degree.

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Figure 1. Relationship between the basic friction angle, the dolomite content and the percentage of fine grains.

(a) Coarse grained limestone (sample 25-1-1)

(b) Fine grained limestone (sample 2-1-1)

(c) Coarse grained dolomite (sample 14-1-1)

(d) Fine grained dolomite (sample 15-1-1)

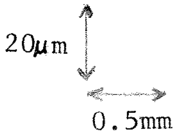

Figure 2. Profiles of rock surfaces of 4 samples lapped by #80 grit.

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