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The interface angle of friction between dry sand and lubricated surfaces

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ABSTRACT

The interface angle of friction between dry sand and various kinds of lubricated construction materials is investigated experimentally with a direct shear test. Nine different construction materials with various surface roughness and five lubricants are utilized. The interface angle of friction between Jahra sand and lubricated construction material is measured for a wide range of normal stresses and different relative densities.

The study shows the effectiveness of using lubricant in reducing the friction between construction materials and sand. The magnitude of the interface angle of friction between sand and lubricated surfaces varies significantly with the surface roughness of the construction material, the viscosity of the lubricant, the relative density of the sand, and the normal stress among other factors. The study also shows that the interface angle of friction increases for some construction material with some types of lubricant.

INTRODUCTION

Many investigators have observed that drilling mud, mainly bentonite, decreases the friction and the bearing capacity of bored piles (Reese *et al.* 1973; Wates & Knight, 1975; Fleming & Sliwinski 1977; Tucker & Reese 1984). Moreover, in pipe jacking projects, when the friction between pipes and surrounding soil becomes very high to overcome, intermediate stations between pits are used and/or lubricant, primarily bentonite, is injected through special holes in the circumference of the pipes (Craig 1983). Although the friction between pipes and the surrounding soil significantly decreases after injecting bentonite, most of the parameters influencing the interface angle of friction between soil and the lubricated surfaces are still unknown.

The interface angle of friction between soil and construction materials was investigated experimentally by various investigators. The laboratory tests were conducted with different experimental models under a wide range of boundary conditions (Potyondy 1961; Das & Seeley 1977; Kulhawy & Peterson, 1979; Dover *et al.* 1982; Ortiz 1982; Chaudhuri & Symons 1983; Mochtar 1985; Tsubakihara *et al.* 1993). None of these tests examined the influence of lubricant on the interface angle of friction between sand and various construction materials. On the other hand, Tatsuoka & Haibara (1985) and Goto *et al.* (1993) studied the shear resistance between sand and smooth or lubricated surfaces. In these studies a rubber membrane smeared with various types of lubrication layers was used to lubricate the ends of a specimen in contact with rigid boundaries.

The main target of this study is to, experimentally, investigate the interface angle of friction (δ) between granular soil and different kinds of construction materials with and without lubricant, in order to identify the most important factors affecting it. Once the various parameters are identified, the best lubricant that causes a maximum reduction in the interface angle of friction between sand and construction materials can be determined. This will lead to better understanding of the role of lubrication in Geotechnical engineering projects.

EXPERIMENTAL PROGRAM

A number of direct shear tests was performed at a constant rate of displacement to determine the interface angle of friction between dry sand and lubricated construction materials. The parameters selected for this investigation are listed in Table (1).

Locally available sand, namely Jahra sand, was utilized in the test. The grain characteristics of this sand are as follows: coefficient of uniformity = 2.8, curvature coefficient = 0.8, specific gravity = 2.64, maximum void ratio = 0.61, and minimum void ratio = 0.37. Three relative densities D_r (40, 70, and 90%) were selected for the tests. The sand specimens were reconstituted and tested dry in all tests.

Nine different construction materials were chosen for this study. These materials were divided into two groups: rough and smooth, as shown in Table (1). The rough surface materials include steel (R.S.), plain concrete (R.P.C.), and cast iron (R.C.I.). The roughness was defined as the relative height between the highest peak and the lowest trough along a surface profile over a 2.5 mm-length (Tatsuoka & Haibara 1995) and was measured using Surtronic 3+ surface texture measurement instrument. The rough materials have surface roughness R_{max} ranges between 40 and 100μm depending on the material type and the method of preparing the surface. The smooth surface materials include steel (S.S.), plain concrete (S.P.C.), cast iron (S.C.I.), Crockery, P.V.C., and Ceramic. The smooth materials have surface roughness R_{max} ranges

Table 1. Summary of the selected parameters.

Sand	Type	Jahra Sand
	D_r (%)	40–70–90
Construction Materials	Rough Group	Steel (R.S.)
		Plain Concrete (R.P.C.)
		Cast Iron (R.C.I.)
	Smooth Group (polished)	Steel (S.S.)
		Plain Concrete (S.P.C.)
		Cast Iron (S.C.I.)
		Ceramic
		Crockery
		P.V.C.
Lubricant	Bentonite Group	10% Bentonite Concentration (B10)
		15% Bentonite Concentration (B15)
	Oil Group	Used Car Oil (Dirty) (D.O.)
		Cars' Oil (20/50) (C.O.)
		Gear Oil (G.O.)
Testing Rate	(mm/min)	0.5–1.0
Normal Stresses	(kPa)	49 98 147 196

Table 2. Summary of the measured surface roughness R_{max} (μm).

	R.S.	R.P.C.	R.C.I.	S.S.	S.P.C.	S.C.I.	Cerm.	Crok.	P.V.C
R_{max}	35	80	92	3.4	17	12	4	9	5.2

between 5 and $20 \mu m$ depending on the material type and the method of surface polishing. The measured surface roughness R_{max} are listed in Table (2).

Five different types of lubricants are utilized in this experimental work as shown in Table (1). The lubricants are divided into two groups: oil and bentonite. The properties of the lubricants used in the experiments are listed in Table (3). These values are measured at the same temperature used for the shear tests, since the lubricant properties are affected by changing the temperature. Liquid and plastic limits are determined for the bentonite and are also listed in Table (3).

TEST PROCEDURE

Because of its simplicity, a deformation-controlled direct shear test is utilized in this experimental study. A box of 100* 100* 20 mm dimensions is used for conducting the shear tests. Two rates of advance of the lower half are selected to be 0.5 and 1.0 mm/min. Normal stresses of 49, 98, 147, 196 kPa are applied to each specimen. In interface tests with or without lubricant the density of sand is determined by sensitive measurement of the weight and the volume of the sand in the box. The test procedure introduced by Potyondy (1961) is utilized in this investigation with some modifications to include the lubrication of the surface of the construction materials. The procedure may be summarized as follows:

1. The construction material is placed in the lower half of the shear box where the upper surface of the construction material is leveled with the top edges of the lower half.
2. To achieve a certain relative density, a specified weight of air dried Jahra sand is placed and compacted in the upper half of the shear box.
3. When a lubricant is used a thin film of the lubricant is applied on the upper surface of the construction materials utilizing a small brush. No attempts had been made to measure the thickness of the lubricant layer before and after running the tests. The sand is then placed on the top of it in the upper half of the shear box.

Thixotropy is the property of suspension of clays to set or to gel when left standing and be restored to a free-flowing liquid when stirred or agitated. Generally, thixotropy gelatin of clay may take hours or days, whereas for bentonite the thixotropy takes only

Table 3. Summary of lubricant properties.

Lubricant	Viscosity (c.p.)	Density (Mg/m^3)	Liquid Limit (%)	Plastic Limit (%)
B10	68	1.040	590	80
B15	180	0.998		
D.O.	522	0.875		
C.O.	3030	0.854		
G.O.	3370	0.908		

a few minutes. Bentonite may change from liquid state to gel state during the test if the test takes a significant time. The bentonite characteristics such as density and viscosity may be changed with time. Therefore, a fresh liquid of bentonite is prepared and is used exclusively for each test.

TEST RESULTS

Direct shear tests are performed for each type of construction material listed in Table (1) with and without lubricant at different relative densities of utilized sand. In this study, the interface angle of friction (δ) is defined as: $\delta = \tan^{-1}(\tau_{max}/\sigma_v)$, where τ_{max} is the maximum shear resistance, and σ_v is the mean vertical stress. The interface angles of friction (δ) are measured and are summarized in Table (4). Many parameters influence the interface angle of friction between dry sand and lubricated surfaces as shown in Table 4. These parameters include lubricant type, surface roughness, relative density of utilized sand, conducting strain rate of the direct shear test, and intensity of normal stresses. Based on the obtained results in this experimental study the influence of the most important parameters affecting the interface angle of friction between dry sand and lubricated surfaces is discussed in the following sections.

Effect of lubricant

As mentioned earlier, lubricants utilized in this experimental work are of two groups (oil and bentonite). These lubricants have different viscosities. The bentonite group which contains two concentrations, 10% and 15%, has a low viscosity compared to that of the oil group as shown in Table 3.

The change in the interface angle of friction (δ) with the viscosity of the lubricant is shown in Fig. 1 for both smooth and rough material surfaces. It is evident from Fig. 1(a) that the interface angle of friction (δ) decreases with the increase of the viscosity of the lubricant for most of the smooth lubricated surfaces. This means that using oil which has high viscosity is more efficient in reducing the interface angle of friction (δ) than using bentonite as a lubricant for smooth surfaces. The maximum reduction of (δ) when oil is utilized instead of bentonite is observed with Ceramic and Crockery, where (δ) decreases from 28° to as low as 13°. However, this observation is not always true for other materials as shown in Fig. 1(a). Changing the viscosity of the lubricant has almost no effect on reducing the interface angle of friction (δ) for both smooth plain concrete (S.P.C.) and the P.V.C.

For the rough lubricated surfaces the viscosity of the lubricant has less significant effect on reducing the interface angle of friction (δ) as shown in Fig. 1(b). The change on (δ) for rough surfaces is only about 5°. With the increase of the lubricant viscosity a small decrease in (δ) is observed until a certain viscosity then (δ) starts to increase again. This behavior is observed for rough steel (R.S.) and for rough cast iron (R.C.I.) as shown in Fig 1(b). However, the rough plain concrete (R.P.C.) shows different behavior where a small increase in (δ) occurs first, then it decreases with the increase of the lubricant viscosity.

Figure 2 shows the lubricant influence factor (a) for different construction materials when different lubricants with different viscosities are applied where

$$a(\%) = \frac{\delta_{with\ lubricant}}{\delta_{without\ lubricant}} * 100$$

Table 4. Summary of test results.

Lubricant	D_r (%)	S.S.	R.S.	S.C.I.	R.C.I.	S.P.C.	R.P.C.	P.V.C.	Ceramic	Crockery
W/O	40	20.7	32.8	23.	35.	28.2	35.5	20.8	19.9	22.1
	70	22.	34.	24.2	37.2	29.7	37.2	26.6	21.	24.4
	90	23.6	35.1	25.4	38.6	31.7	38.7	27.7	23.	26.
G.O.	40	12.3	29.8	16.7	29.9	25.1	30.2	17.8	14.1	16.6
	70	13.7	31.3	17.5	30.8	26.2	31.6	19.5	15.6	17.3
	90	14.7	32.8	18.9	31.9	27.2	33.	20.6	18.4	18.6
C.O.	40	15.2	27.2	16.	28.9	27.6	32.5	20.6	12.7	15.7
	70	16.6	29.3	16.6	30.1	28.7	33.	21.3	15.1	17.7
	90	18.3	31.3	17.7	31.	29.4	34.2	22.	16.2	22.
D.O.	40	13.7	25.8	15.8	27.5	24.6	32.	19.8	13.1	15.8
	70	15.6	26.4	17.3	28.2	25.8	33.6	22.3	15.9	18.8
	90	16.5	28.1	18.9	29.2	26.7	35.6	24.7	19.	20.4
B15	40	21.7	28.5	21.9	29.6	28.6	29.	17.5	28.2	27.9
	70	22.2	29.3	22.9	31.1	29.5	30.2	18.8	29.2	29.2
	90	22.6	30.4	23.6	32.	30.5	31.7	19.9	31.3	30.5
B10	40	21.3	30.4	20.8	29.1	26.9	28.7	18.1	28.9	27.9
	70	22.5	31.1	21.6	31.4	28.8	30.1	19.	30.6	29.6
	90	23.2	31.6	22.5	32.6	29.2	31.7	20.3	31.9	30.7

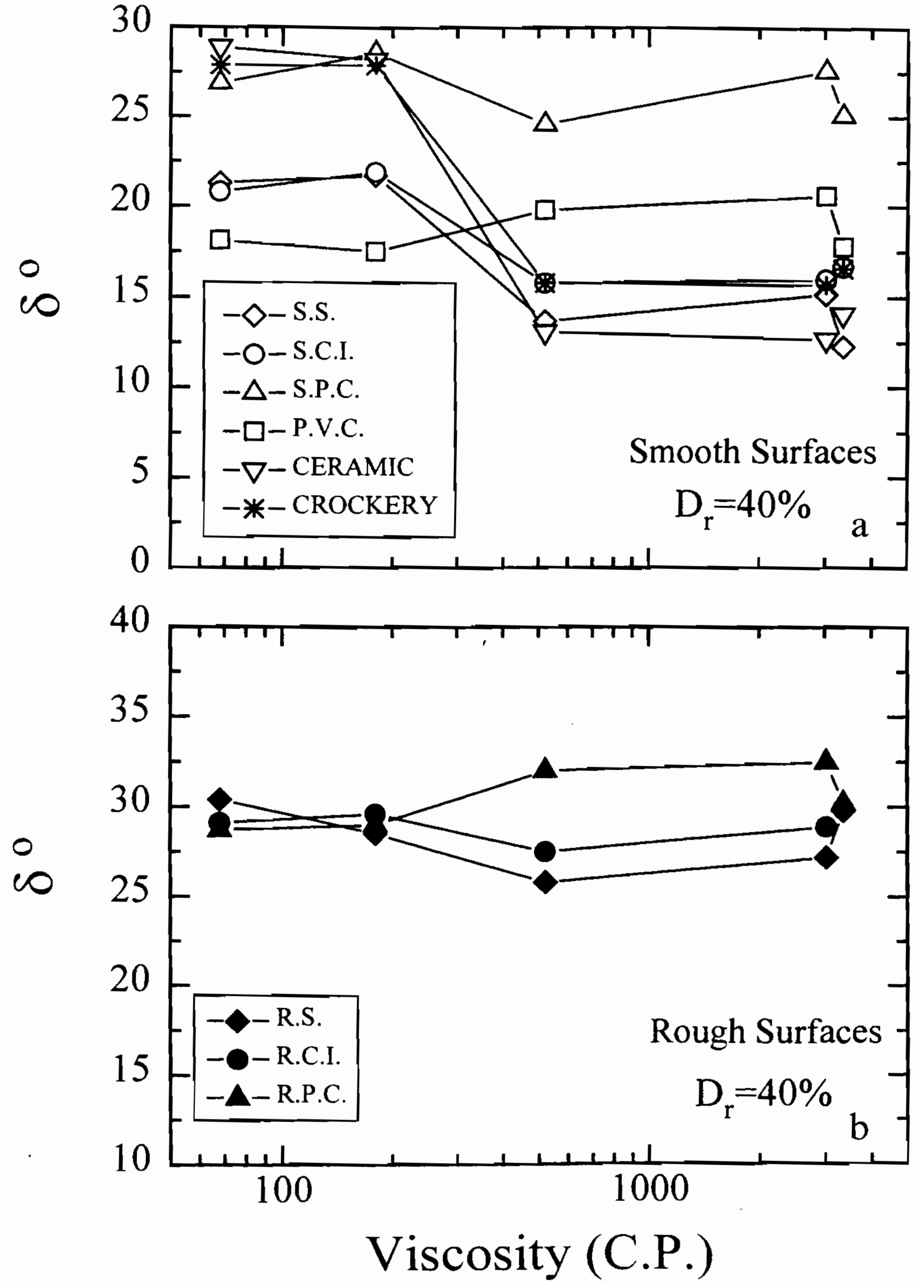

Fig. 1 (a&b). The effect of lubricant viscosity on the interface angle of friction (*δ*).

The percentage of the reduction in (*δ*) due to the application of the lubricant may be given as (100 – *a*)%. For example, (*a*) ranges between 98% and 60% for the oil lubricant group (D.O., C.O., and G.O.) as shown in Fig. 2. This means that the

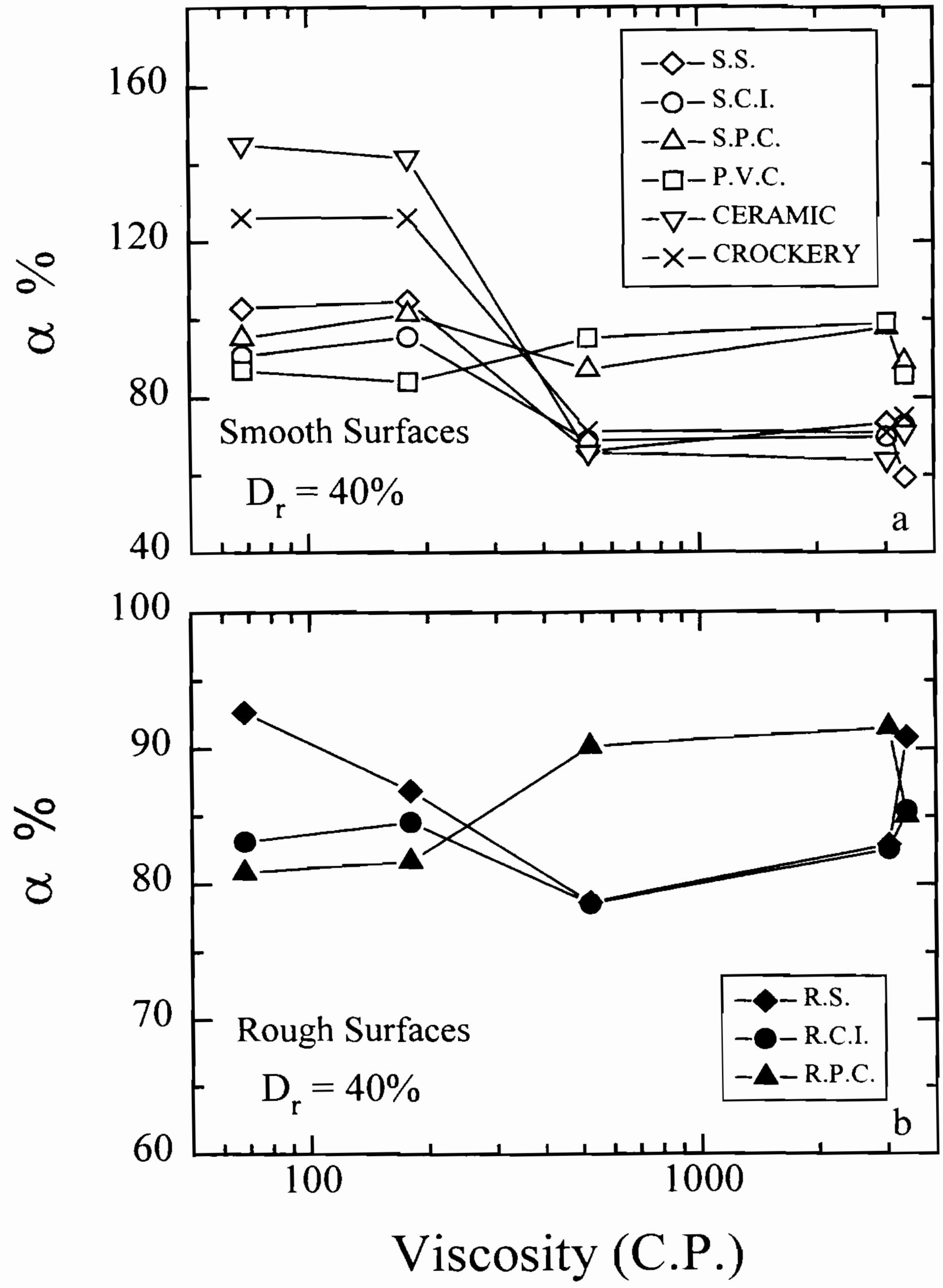

Fig. 2 (a&b). The effect of lubricant viscosity on the lubricant influence factor (α).

percentage of the reduction on (δ) due to oil lubricant ranges between 2% and 40% depending on the material surface roughness.

In spite of the fact that most lubricants reduce the interface angle of friction (δ), still a certain number of lubricants does not show that effect, as shown in Fig. 2(a). This was noted for the two types of bentonite (B10 and B15) where they increase (δ) between Crockery and Jahra sand as shown in the figure. Moreover, the bentonite lubricant with Ceramic shows the maximum inverted results where the interface angle of friction increases by 45% of its value without lubricant. Meanwhile, P.V.C. shows the best results with bentonite where the reduction of the interface angle of friction is about 18%.

The results in Fig. 3 show that the value of (a) depends on the relative density of utilized sand. For P.V.C. Fig. 3(a) shows that (a) decreases with the increase of the density of sand in all types of lubricants. This figure shows that at higher sand density the lubricant has a significant effect on reducing the interface angle of friction. Meanwhile, in the case of Ceramic, (a) tends to be higher than 130% with bentonite for all relative densities as shown in Fig. 3(b). The oil lubricant group, on the other hand, tends to reduce the interface angle of friction for all relative densities although (a) is not significantly affected by the wide range of oil viscosities. In the case of smooth steel similar results are obtained as shown in Fig. 3(c). However, in the case of the bentonite group, (a) tends to be higher than 100% at relative density less than 70%, and becomes lower than 100% at higher densities.

Effect of Surface Roughness

From Table 5 and Fig. 2 it can be noted that (a) in the case of rough surfaces is not affected very much by the type of lubricant group. The average (a) is about 86 % due to the oil lubricant group (D.O., C.O., and G.O.) and this average is about 89% due to bentonite lubricant group (B10 and B15). This means that for rough surfaces both oil and bentonite have nearly the same effect on reducing the interface angle of friction. Meanwhile, for the smooth surfaces, the reduction in the interface angle of friction depends on the lubricant type. From the values shown in Table 5 it may be concluded that for the smooth surfaces the oil lubricant is more effective in reducing the interface angle of friction (δ) than bentonite.

For smooth and rough surfaces the relationship between the interface angle of friction (δ) and the viscosity of the lubricant at different relative densities is shown in Fig. 4. Clearly the rough surfaces give a higher interface angle of friction (δ) than the smooth surfaces for all viscosities. The results also show that the interface angle of friction (δ) depends on the relative density of the utilized sand for both smooth and rough surfaces. The interface angle of friction between lubricated surfaces and dense sand is always greater than that between lubricated surfaces and loose sand.

In spite of the fact that smooth plain concrete (S.P.C.) has an appreciable smooth surface, its behavior is similar to one of the rough surface groups as shown in Fig. 4(c). Therefore, it is very important to consider any concrete surface as a rough one for practical purposes.

Table 5. Ranges of (a) for smooth and rough surfaces (Dr = 40%).

	a (%)	
	Bentonite	Oil
Rough	86.3–93	77.6–93.5
Smooth	70.7–145.7	59.6–98.9

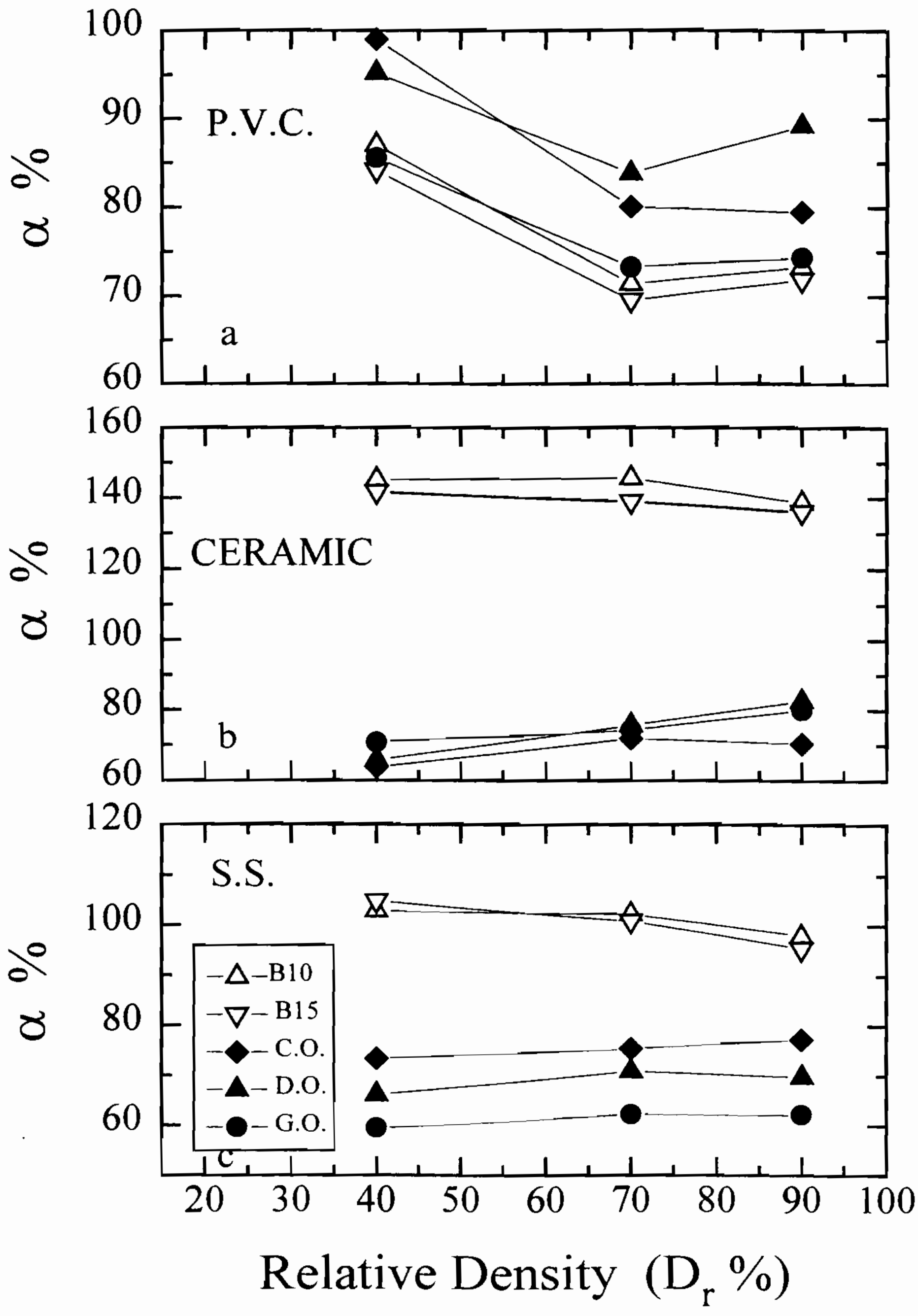

Fig. 3. The relationship between (α) and the relative density (D_r %).

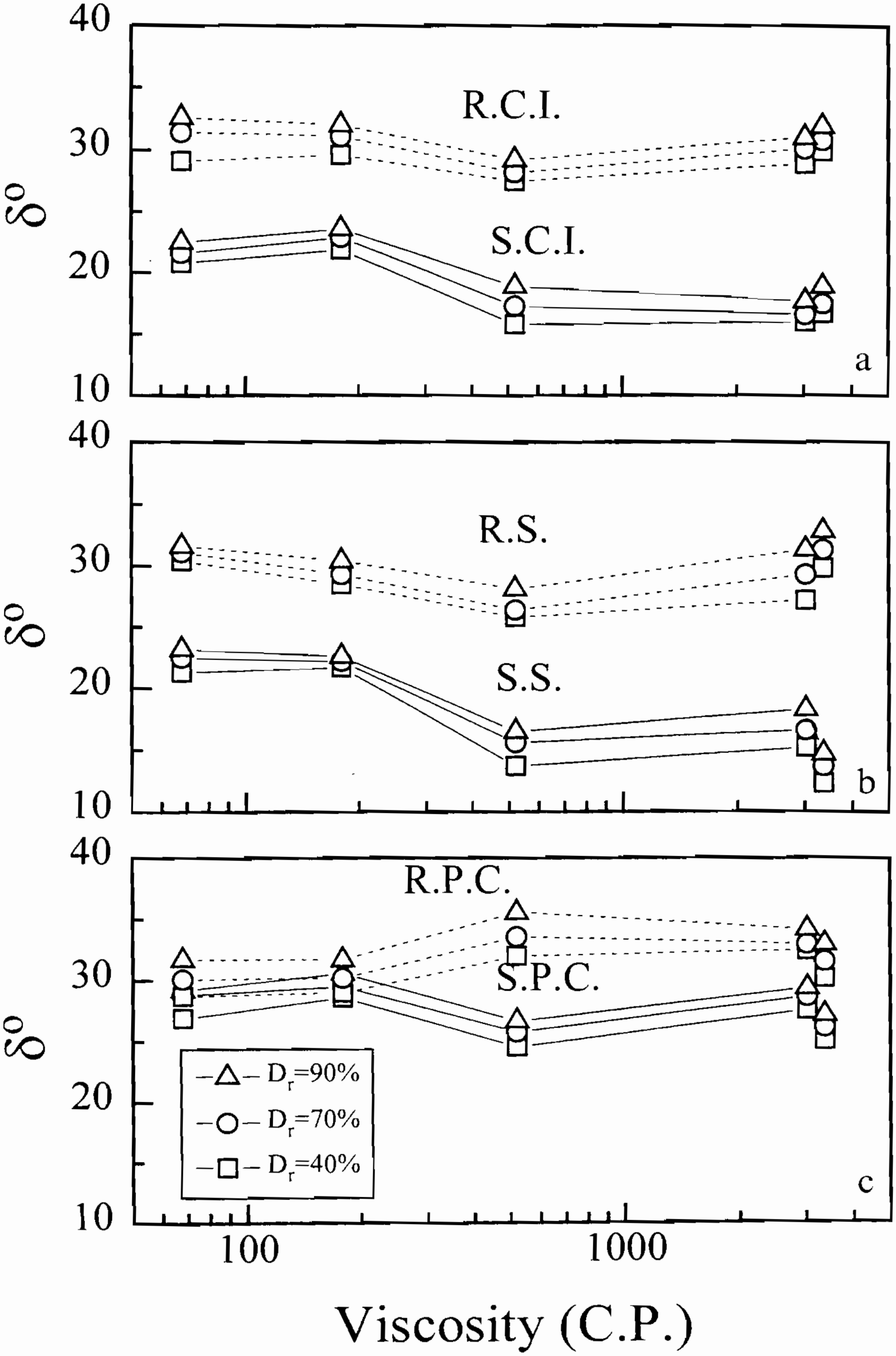

Fig. 4. The effect of surface roughness on (δ).

The effect of the lubricant in reducing the interface angle of friction (δ) for rough and smooth surfaces is shown in Fig. 5. It shows the ratio between (δ) and the angle of internal friction of the utilized sand (φ) for all test results with and without lubricant in both surface groups, smooth and rough. Without lubricant (δ/φ) ranges between 0.57 and 0.82 for smooth surface and between 0.82 and 1.0 for rough surfaces. However, when the lubricant is utilized on most of the smooth surfaces the ratio (δ/φ) is reduced and ranges between 0.38 and 0.7. Some of the materials, such as smooth plain concrete and both Crockery and Ceramic with low lubricant viscosity, behave similarly to the rough surface material group with lubricant. It is also evident from these results that the reduction in the ratio (δ/φ) is not significant for rough surfaces with lubricants.

Tsubakihara *et al.* (1993) classified the failure modes between the interface and the soil into three different modes as shown in Fig. 6. In Mode (1) shear failure occurs within the soil mass; in Mode (2) full sliding occurs at the interface, while in Mode (3) sliding displacement and shear strain increase simultaneous. In the final failure Mode (3) will be similar to either Mode (1) or Mode (2). The mixed behavior of Mode (3) can be seen in moderate steel roughness with sand-clay mixes. In the existence of the lubricant on the interface it is difficult to expect that Mode (1) may occur. Therefore, the idealized classification for the failure modes may be reduced to two modes only (Mode 2 and Mode 3), as shown in Fig. 7. Further investigation is needed to validate such idealization for the failure modes. These failure modes depend on both the surface roughness as well as the viscosity of the lubricant.

It is well-known that the volume change in dense sand during the shear tests tends

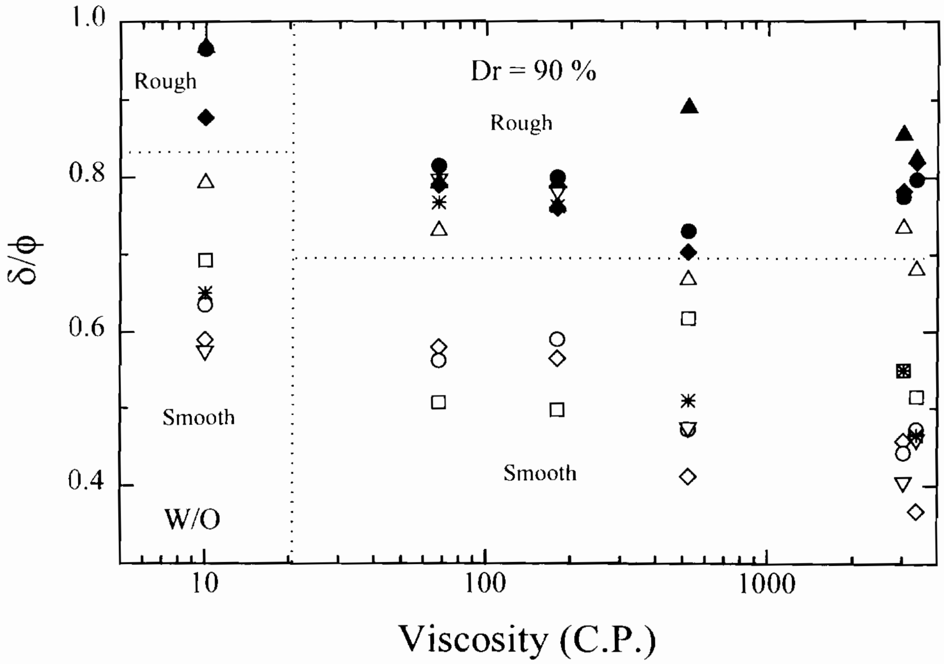

Fig. 5. The effect of the lubricant in reducing the interface angle of friction for rough and smooth surfaces.

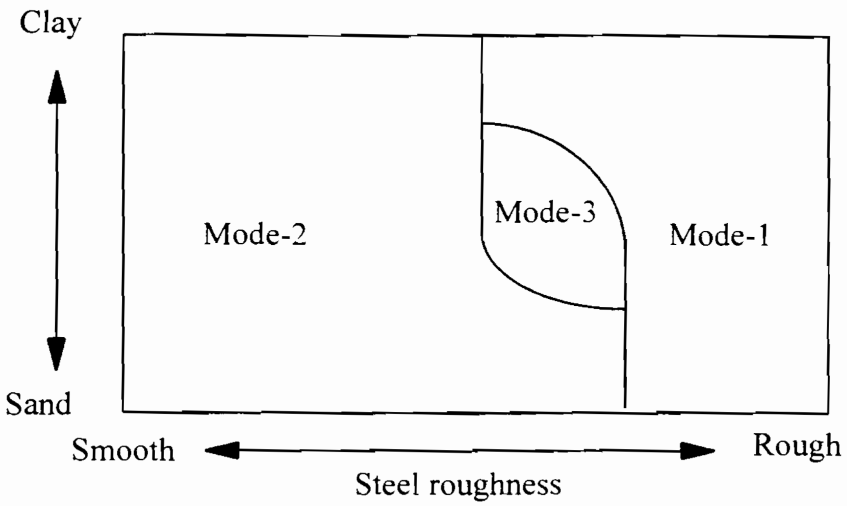

Fig. 6. Idealized classification of the failure modes (without lubricant).

to dilate (to increase in volume), whereas the loose sand tends to compress (to decrease in volume). Figures 8 & 9 show the stress-strain curves for rough and smooth steel surfaces with and without lubricant for dense sand. In the case of rough steel (R.S.) the peak shear strength is clear in both cases with and without oil (C.O.) as shown in Fig. 8. However, in the case of bentonite (B10) there is no well-defined peak. Not only the stress-strain relationship is affected by the existence of the lubricant in the interface, but the volume change as well. Both types of lubricants, (C.O.) and bentonite, tend to decrease the amount of dilation during the shear tests as shown in Fig. (8). On the other hand, Fig. 9 shows that there is no well-defined peak in the case of smooth steel (S.S.)

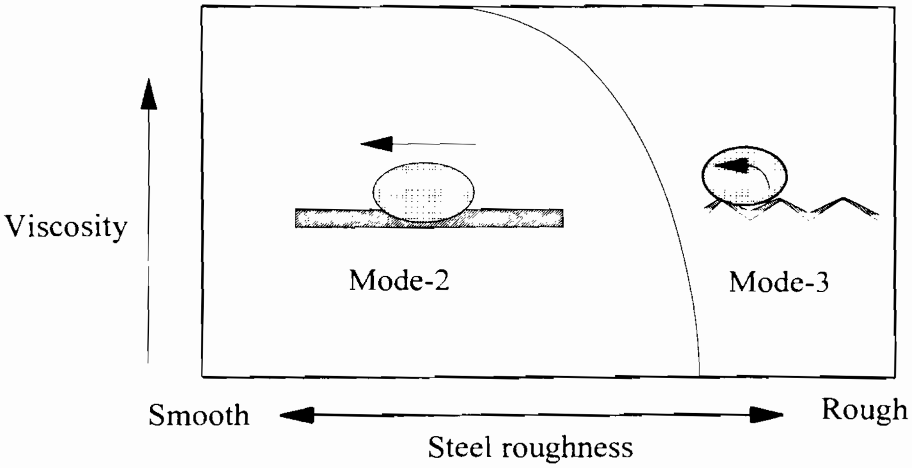

Fig. 7. Idealized classification of the failure modes (with lubricant).

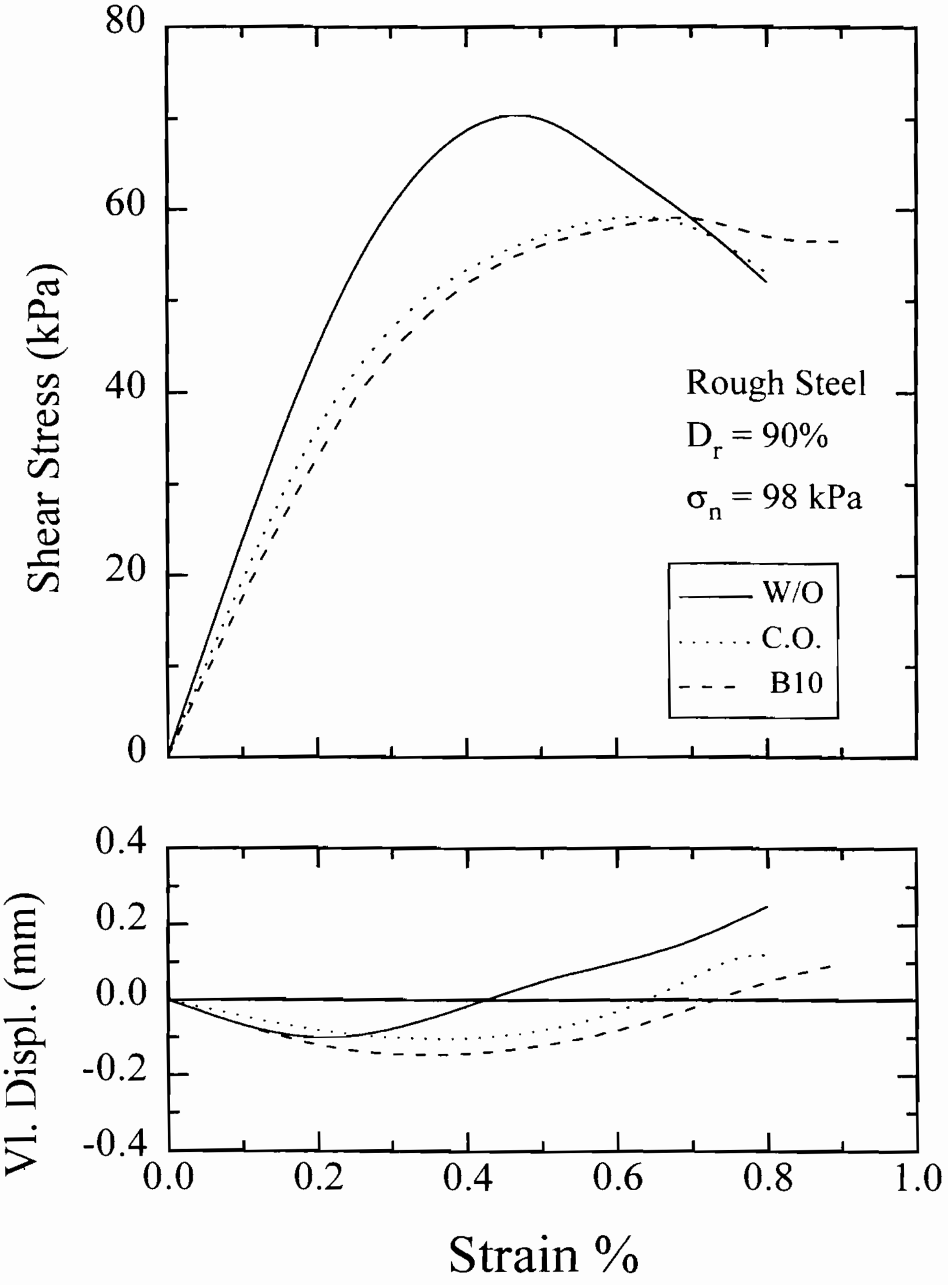

Fig. 8. Stress-strain relationship for lubricated rough surfaces.

with or without lubricant. The figure also shows that Jahra sand tends to compress (decrease in volume) during shear tests for all types of lubricant.

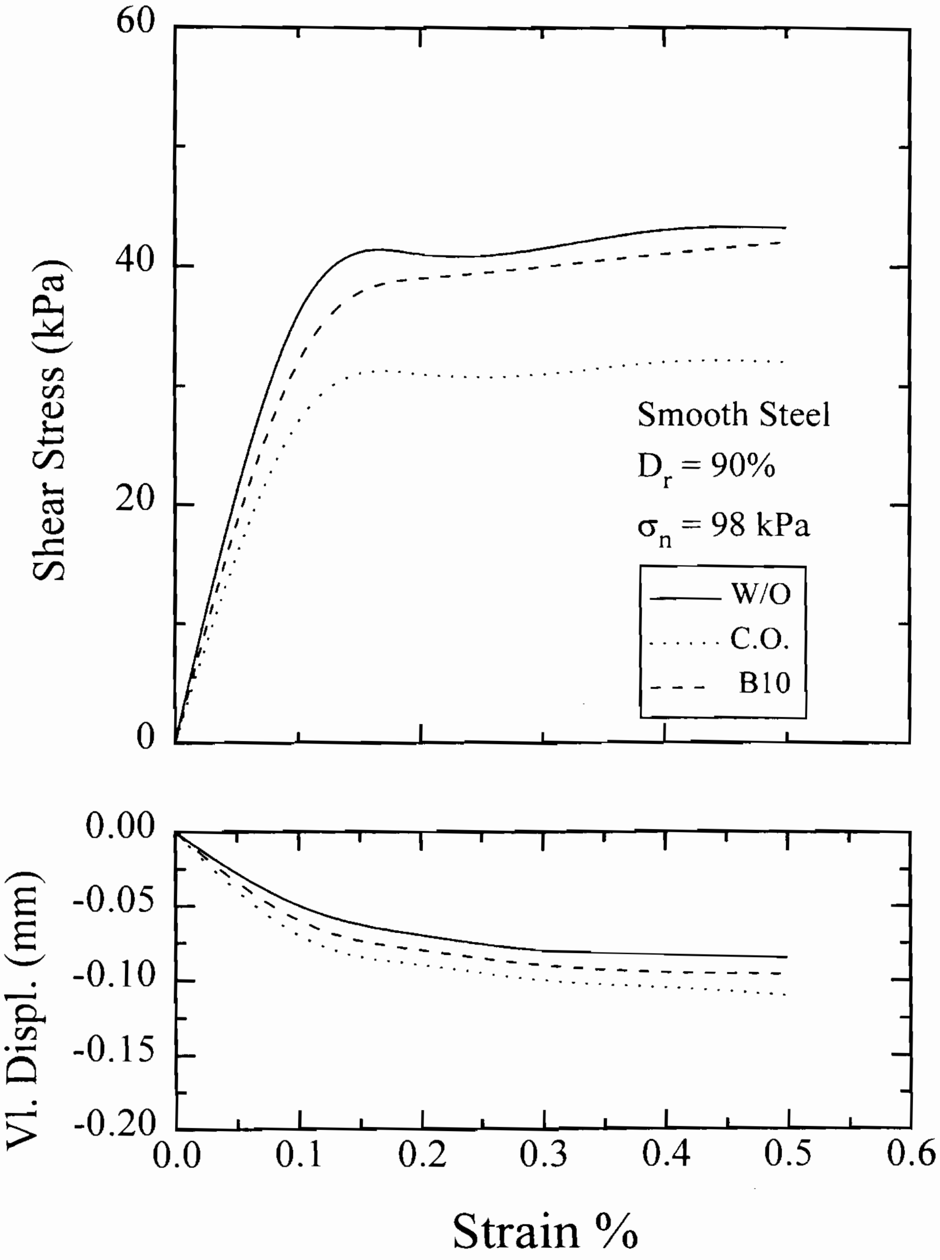

Fig. 9. Stress-strain relationship for lubricated smooth surfaces.

Effects of Other Factors

To study the effects of normal stresses the interface angle of friction (δ) at normal stress equals 49 kPa is compared with that obtained at normal stress equals 196 kPa for all performed tests. From these comparisons it is observed that (δ) at normal stress of 49 kPa is greater than the one at 196 kPa normal stress in about 70% of the total number of tests. 15% of the tests yielded an opposite result. Generally, this happens for smooth surfaces with low sand densities. The rest of the tests have no clear correlation under different normal stresses. Moreover, the stress-strain relationship shows a very interesting behavior under different normal stresses. For low normal stress levels there is no clear peak in the stress-strain curves in all cases (rough or smooth, dense or loose state, and with or without lubricants). On the other hand, for high normal stress a defined peak is observed in very dense sand especially in the case of rough surfaces with and without lubricant. However, in the case of smooth surfaces, no clear peak can be observed.

To study the effect of the rate of shearing on the interface angle of friction direct shear tests are performed with two rates of strain: 0.5 and 1 mm/min. Experiments have shown that within the investigated range the effect of rate of strain on the interface angle of friction is always less than 5% and 3% for the smooth and the rough surfaces, respectively.

CONCLUSIONS

Based on the experimental results the following conclusions could be drawn:

1. Many parameters influence the interface angle of friction (δ) between sand and various materials. These parameters include lubricant type, surface roughness, relative density of utilized sand, conducting strain rate of the direct shear test, and intensity of normal stresses.
2. In spite of the fact that most lubricants reduce the interface angle of friction (δ), bentonite increases (δ) of Crockery and Ceramic. Moreover, the bentonite lubricant with Ceramic shows the maximum inverted results where the interface angle of friction increases by 45% of its value without lubricant.
3. For smooth surfaces oil is more efficient in reducing the interface angle of friction (δ) than bentonite, while for rough lubricated surfaces the viscosity of the lubricant has less significant effect on reducing the interface angle of friction (δ).
4. The value of both the interface angle of friction (δ) and the lubricant influence factor (a) depend on the relative density of the sand utilized for both smooth and rough surfaces. At higher sand density the lubricant has a significant effect on reducing the interface angle of friction.
5. For rough surfaces both oil and bentonite have nearly the same effect on reducing the interface angle of friction, while for smooth surfaces the reduction in the interface angle of friction depends on the lubricant type.
6. The rough surfaces give higher interface angle of friction (δ) than the smooth surfaces for all viscosities.
7. The lubricant influence factor (a) is not significantly affected by the wide range of oil viscosities.
8. The reduction in the ratio (δ/φ) due to utilizing lubricant is more significant for smooth surfaces than for rough surfaces with lubricants.

9. The failure modes are idealized into two modes: Mode (2) and Mode (3). In Mode (2) full sliding occurs at the interface, while in Mode (3) sliding displacement and shear strain increase simultaneous. Further investigations are needed to validate such idealization for the failure modes. These failure modes depend on both the surface roughness as well as the viscosity of the lubricant.
10. Not only the stress-strain relationship is affected by the existence of the lubricant in the interface, but the volume change as well. In the case of rough surfaces lubricants tend to decrease the amount of dilation during the shear tests, while in the case of smooth surfaces sand tends to compress (decrease in volume) during shear tests for all types of lubricant. The results also show that there is no well-defined peak in the case of smooth surfaces with or without lubricant.
11. The interface angle of friction (δ) is affected by the normal stress level. At low normal stress levels (δ) tends to be greater than that at high normal stress levels in most cases. Moreover, the stress-strain relationship shows different behavior under different normal stresses. For low normal stress levels there is no clear peak in the stress-strain curves in all cases (rough or smooth, dense or loose state, and with or without lubricants). On the other hand, for high normal stress a defined peak is observed in very dense sand, especially in the case of rough surfaces with and without lubricant. However, in the case of smooth surfaces no clear peak can be observed.
12. Experiments have shown that within the investigated range the effect of rate of strain on the interface angle of friction is always less than 5% and 3% for the smooth and the rough surfaces, respectively.

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معامل الإحتكاك بين الرمل الجاف وأسطح مدهونة بمواد مقللة للإحتكاك

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خلاصة

يقوم هذا البحث على دراسة معامل الإحتكاك بين الرمل الجاف وأسطح مصنعة من مواد إنشائية متنوعة ومدهونة بمواد مقللة للإحتكاك وذلك عن طريق فحص القص المباشر.

وقد تم فحص تسعة أنواع من المواد الإنشائية ذات أسطح مختلفة الخشونة وبإستعمال خمسة أنواع من المواد المقللة للإحتكاك. حيث تم قياس معامل الإحتكاك لعدة كثافات نسبية للرمل تحت تأثير مجال واسع من الإجهادات الشاقولية.

وقد بينت الدراسة فعالية إستعمال المواد المقللة للإحتكاك بين الأسطح المختلفة والرمل. وقد بينت الدراسة أن معامل الإحتكاك يختلف بدرجات متفاوتة وذلك تبعاً لعدة عوامل منها: ـ تأثير خشونة السطح، ولزوجة المواد المقللة للإحتكاك، والكثافة النسبية للرمل والإجتهادات الشاقولية.

وقد بينت الدراسة أيضاً أن عامل الإحتكاك قد يزيد بعض المواد الإنشائية عند إستخدام أنواع معينة من المواد المقللة للإحتكاك.