

COEFFICIENT OF FRICTION MEASUREMENT BETWEEN CABLE AND
CONDUIT SURFACES UNDER VARYING NORMAL LOADS

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Abstract

Static and kinetic coefficients of friction between cable and conduit surfaces are measured under high normal loads using a specially designed friction table. The performance of cable lubricants under high loads is evaluated and compared to performance under low normal loads. Preliminary findings indicate that the results may be used to better predict cable pulling tensions in field cable installations and to aid in the design of conduit systems.

INTRODUCTION

Tension exerted on cables during installation is a major consideration in the design of conduit systems. Specifically, the total length and number of bends in a duct system are limited by the maximum tension and sidewall pressures recommended by cable manufacturers and accepted industry practice. A number of studies have been done to better define limits on sidewall pressure. This paper does not go into this area, other than to note that there is a high expectation that there are such limits for optimal cable life.

Most of the tension and resulting sidewall pressure observed during a cable pull is the result of friction between the cable jacket and conduit surfaces. Mathematical equations derived by R. C. Rifenberg [1] can be used to estimate the expected tension for a given cable/conduit system. These equations include a measure of friction which is the dimensionless "coefficient of friction".

To date, coefficient of friction values have been measured by variations of an inclined plane method. In such measurements, the bearing force between the cable and conduit is equal to the weight of the cable, which is usually less than 73 N/m (5 lbf/ft). However, in actual cable pulling, the bearing force around corners can be hundreds of times higher than the weight of the cable. This difference affects the real coefficient of friction. Coefficient of friction values determined on an inclined plane have shown limited accuracy as predictors of actual cable pulling tensions when used in mathematical equations.

This paper describes a new method of coefficient of friction measurement between conduits and cables under high normal loads. It evaluates the performance of cable lubricants under these conditions. The results indicate the possible design of longer, more complex duct systems although additional correlation with friction measurements in field cable pulls is necessary.

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THEORY

The static coefficient of friction, μ_s , is a proportionality constant between the minimum pulling force required to start an object in motion, f_s , and the normal force, N , between the object and adjacent surface

$$f_s = \mu_s N \quad (1)$$

The frictional force opposing the pulling force is due to the bonding of the molecules of the object and the adjacent surface at places where the surfaces are in very close contact. For unlubricated surfaces, the pulling force required to move an object has been found experimentally to be approximately independent of the area of contact between the two surfaces and directly proportional to the normal force exerted by one surface on the other [2].

The kinetic coefficient of friction, μ_k , is a proportionality constant between the minimum force required to keep an object in motion, f_k , and the normal force between the object and adjacent surface, N .

$$f_k = \mu_k N \quad (2)$$

It has been found that the kinetic coefficient of friction is:

1. Less than the static coefficient of friction.
2. Dependent on the relative speed of the surfaces, [but for speeds from 1 cm/sec to 7 m/sec (2 ft/min to 1400 ft/min) μ_k is approximately constant].
3. Dependent on the nature of the surfaces.
4. Independent of the macroscopic area of contact.

Lubricants

The above experimentally determined characteristics of the coefficient of friction are true for unlubricated surfaces only. Lubricants drastically affect the coefficients of static and kinetic friction when they are introduced as a thin film between two solid surfaces. This film separates the bonding molecules of the two surfaces and creates a slip plane upon which the surfaces slide. The performance of lubricants under various conditions varies significantly because of the microscopic nature of friction. Some lubricants perform well between certain types of materials while others do not. The same holds true for performance under high normal loads. Some lubricants tend to get squeezed out under high normal loads, which reduces or eliminates their ability to lower friction. Other lubricants will tear or break down under high shear conditions, also making them less effective.

Coefficient of Friction Measurement

Inclined Plane Method (Low Normal Loads) - Static and kinetic coefficients of friction can easily be measured by placing a block on a plane surface and inclining the plane until the block begins to slide.

At angles less than the critical angle, θ_c , (the angle at which sliding starts), the block is in static equilibrium under the influence of its weight, mg , the normal force, N , and the force of static friction, f_s .

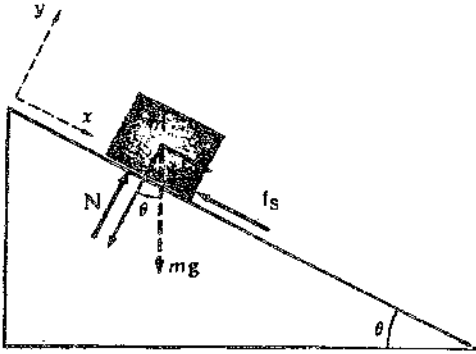


Fig. 1 Forces exerted on a block resting on an inclined plane

If the x-axis is chosen parallel to the plane and the y-axis perpendicular to the plane, force balances yield:

$$\sum F_y = N - mg \cos \theta = 0 \tag{3}$$

$$\sum F_x = mg \sin \theta - f_s = 0 \tag{4}$$

which can be simplified by eliminating the weight from these two equations

$$mg = N / \cos \theta \tag{5}$$

$$f_s = mg \sin \theta \tag{6}$$

to yield:

$$f_s = N \sin \theta / \cos \theta = N \tan \theta \tag{7}$$

At the critical angle, θ_c , the static frictional force is limiting and f_s can be replaced by $\mu_s N$ [Equation (1)],

The coefficient of static friction is then just the tangent of the critical angle.

$$\mu_s = \tan \theta_c \tag{8}$$

At angles greater than the critical angle, the block slides down the incline with acceleration a_x . The kinetic frictional force, f_k , is then $\mu_k N$ [Equation (2)] and a force balance in the x direction yields:

$$\sum F_x = mg \sin \theta - \mu_k N = ma_x \tag{9}$$

The normal force, N , may be substituted since

$$N = mg \cos \theta \tag{10}$$

which yields:

$$\sum F_x = ma_x = mg \sin \theta - \mu_k mg \cos \theta \tag{11}$$

From the position equation of projectile motion in the x plane

$$x = x_0 + v_{0x}t + a_x t^2 / 2 \tag{12}$$

a projectile launched from a zero position ($x = 0$) and with no initial velocity ($v_{0x} = 0$) and acceleration a_x results in the equation:

$$x = a_x t^2 / 2 \tag{13}$$

or solved for acceleration yields:

$$a_x = 2x / t^2 \tag{14}$$

where:

- a_x = acceleration in x direction
- x = distance traveled
- t = time to travel x distance

If the incline is at an angle greater than the critical angle and the block is started from rest, the time it takes to travel a distance, x , can be timed and the acceleration determined. Substitution of Equation (14) into Equation (11) yields:

$$m 2x / t^2 = mg \sin \theta - \mu_k mg \cos \theta \tag{15}$$

Eliminating the mass and solving for μ_k results in the equation

$$\mu_k = \tan \theta - 2x / (gt^2 \cos \theta) \tag{16}$$

which can be used to calculate the coefficient of kinetic friction.

Friction Table Method (High Normal Loads) - The static coefficient of friction is determined by measurement of the normal force between two surfaces and the minimum pulling force required to start the object in motion.

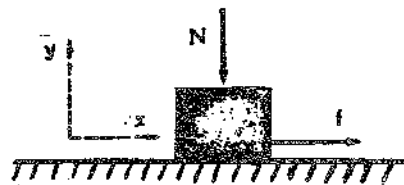


Fig. 2 Block on horizontal surface.

The static coefficient of friction, by definition, is then determined:

$$\mu_s = f_s / N \tag{17}$$

The kinetic coefficient of friction may be determined by measurement of normal force between two surfaces and the minimum kinetic pulling force required to keep the object in motion. The kinetic coefficient of friction, by definition, is then determined:

$$\mu_k = f_k / N \tag{18}$$

EXPERIMENTAL

Inclined Plane Method

The inclined plane method can be directly applied to the cable/conduit systems by using a conduit section split lengthwise as the "inclined plane" and a cable section as the "block". Any type of conduit or cable can be used.

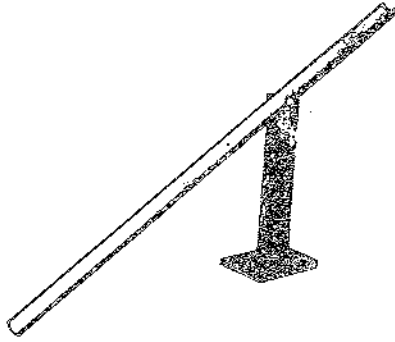


Fig. 3 Inclined plane apparatus

The experimental apparatus used for the inclined plane method is shown in Fig. 3. It consisted of:

1. 3 - 2.31 m (7.58 ft) lengths of 7.62 cm (3 in) inner diameter conduits cut lengthwise.
2. 1 - Wood stand
3. 3 - 15.2 cm (6 in) length sections of cable
4. 1 - Stop watch

Static Coefficient of Friction - The experimental procedure employed was as follows:

1. A thin coat of lubricant (1 to 2 mm) was spread evenly on both the cable and conduit.
2. The conduit was tilted upward from horizontal until the cable section started in motion.
3. The angle of inclination was recorded.

Kinetic Coefficient of Friction - The experimental procedure employed was as follows:

1. A thin coat of lubricant (1 to 2 mm) was spread evenly both on the cable and conduit (conduit was tilted to 30 degrees from horizontal).
2. The cable section was placed at the starting line 31 cm (12.2 in) from the top of the conduit and released while simultaneously starting the stop watch.
3. The stop watch was stopped when the cable reached the end of the conduit and the time recorded.

Friction Table Method

The friction table method of friction measurement can be directly applied to cable/conduit systems by using a conduit section cut lengthwise as the "horizontal plane" and a cable section as the "block". Any type of conduit or cable can be used.

The experimental apparatus used to determine the coefficient of friction is shown in Fig. 4.

The friction table consists of:

1. Sidewall Cylinder - an air cylinder mounted vertically which applies a controlled normal force to a 15.2 cm (6 in) cable section.
2. Pulling Cylinder - an air cylinder mounted horizontally which applies a controlled pulling force to a frictionless cart/conduit section.
3. Necessary valving and controls to regulate the two cylinders.

A 15.2 cm (6 in) boot is attached to the end of the vertically mounted sidewall cylinder which evenly applies and distributes a normal load over the entire 15.2 cm (6 in) cable section and also holds the cable section stationary.

A 48.3 cm (19 in) conduit section split lengthwise is securely fastened to the frictionless cart so as to become a rigid single unit attached to the horizontally mounted pulling cylinder. The pulling cylinder moves the cart/conduit under the stationary cable section.

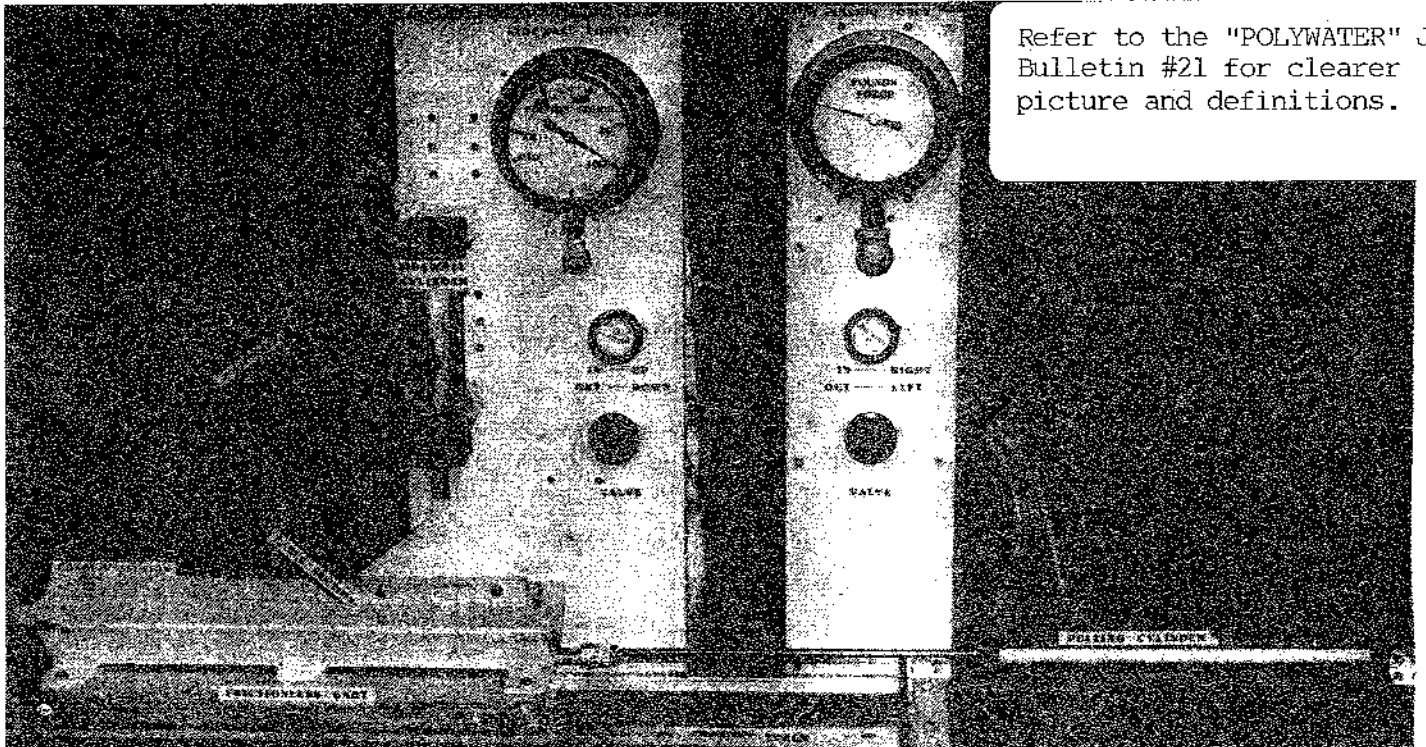


Fig. 4. Friction table device

Any cable section 15.2 cm (6 in) long and up to 6.4 cm (2.5 in) outside diameter may be placed in any conduit section 48.3 cm (19 in) long and 5.1 to 7.6 cm (2 to 3 in) inner diameter for coefficient of friction measurement.

The scales for the two air cylinders were carefully calibrated to give accurate readings [sidewall cylinder $\pm 3\%$ at 445 N (100 lbf), pulling cylinder $\pm 5\%$ at 147 N (33 lbf)].

The experimental procedure employed was as follows:

1. A thin coat of lubricant (1 to 2 mm) was spread evenly both to the cable and conduit.
2. The 15.2 cm (6 in) cable section was placed in the conduit under the sidewall cylinder.
3. A maximum normal force ranging from 580 to 2920 N (40 to 200 lbf) per lineal meter (ft) of cable length was applied by the sidewall cylinder to the 15.2 cm (6 in) cable. Smaller normal forces were required to measure high coefficients of friction due to the strength limitations of the pulling cylinder [147N (33 lbf)].

Static Coefficient of Friction - The minimum pulling force required to start the cart/conduit in motion under the cable was determined by:

1. Applying a small pulling force to the cart/conduit.
2. Increasing the pulling force until the cart/conduit started in motion.
3. Recording the final pulling force.

Kinetic Coefficient of Friction - The minimum pulling force required to keep the cart/conduit in motion under the cable was determined by:

1. Applying a pulling force to the cart/conduit.
2. Starting the cart/conduit in motion with a tap from a rubber mallet.
3. Adjusting the pulling force until the cart/conduit maintained a constant velocity.
4. Recording the final pulling force.

The basic types of cable lubricants tested were:

- 1) Control-Unlubricated (Bare)
- 2) High performance gel polymer solution (HPGP)
- 3) Gel polymer solution (GP)
- 4) Liquid polymer solution (LP)
- 5) Wax emulsion (WE)
- 6) Fluffed soap (FS)
- 7) Bentonite clay (BC)
- 8) Talcum powder (TP)

SUMMARY OF RESULTS

Table I Coefficients of Friction (Inclined plane method)

| Cable | Conduit Lube | PVC | | Rigid | | EMT | |
|----------|-----------------|---------|---------|---------|---------|---------|---------|
| | | μ_s | μ_k | μ_s | μ_k | μ_s | μ_k |
| XLP | WE | .21 | .20 | .20 | .20 | .30 | .25 |
| | LP | .32 | .30 | .29 | .26 | .23 | .19 |
| | HPGP | .34 | .34 | .42 | .42 | .50 | .50 |
| | FS | .52 | .52 | .45 | .41 | .46 | .46 |
| | TP | .50 | .42 | .56 | .50 | .60 | .52 |
| | GP | .44 | .44 | .42 | .38 | .48 | .48 |
| | BC | .83 | .83 | .90 | .90 | 1.0 | 1.0 |
| | Bare | .60 | .52 | .44 | .44 | .48 | .48 |
| PVC | WE | .26 | .26 | .22 | .20 | .32 | .30 |
| | LP | .42 | .27 | .34 | .27 | .36 | .27 |
| | HPGP | .50 | .50 | .42 | .42 | .55 | .50 |
| | FS | .50 | .50 | .40 | .35 | .46 | .46 |
| | TP | .55 | .50 | .52 | .50 | .60 | .52 |
| | GP | .50 | .45 | .47 | .45 | .73 | .37 |
| | BC | .80 | .80 | .90 | .90 | 1.0 | 1.0 |
| | Bare | .40 | .30 | .27 | .27 | .30 | .30 |
| Hypalon* | WE | .32 | .28 | .30 | .27 | .36 | .28 |
| | LP | 1.5 | .19 | .66 | .26 | .50 | .25 |
| | HPGP | .35 | .35 | .38 | .38 | .44 | .44 |
| | FS | .45 | .45 | .42 | .42 | .64 | .62 |
| | TP | .50 | .47 | .50 | .50 | .60 | .55 |
| | GP | 1.0 | .85 | .38 | .38 | .80 | .70 |
| | BC | .77 | .77 | 1.7 | 1.2 | 1.2 | 1.2 |
| | Bare | 2.0 | 1.1 | 1.5 | 1.0 | 1.7 | 1.0 |

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Table II Coefficients of Friction (Friction table method)

| Cable | Conduit Lube | PVC | | | Rigid | | | EMT | | |
|----------|-----------------|-----|---------|---------|-------|---------|---------|-----|---------|---------|
| | | N | μ_s | μ_k | N | μ_s | μ_k | N | μ_s | μ_k |
| XLP | HPGP | 100 | .15 | .12 | 100 | .15 | .14 | 100 | .16 | .16 |
| | WE | 100 | .09 | .09 | 100 | .15 | .14 | 100 | .17 | .17 |
| | FS | 100 | .12 | .12 | 100 | .17 | .17 | 100 | .28 | .25 |
| | GP | 100 | .22 | .21 | 100 | .25 | .24 | 100 | .29 | .28 |
| | BC | 100 | .24 | .24 | 100 | .25 | .25 | 100 | .30 | .30 |
| | LP | 100 | .28 | .27 | 100 | .27 | .25 | 100 | .32 | .32 |
| | TP | 80 | .40 | .40 | 40 | .62 | .60 | 60 | .43 | .43 |
| | Bare | 40 | .75 | .71 | 40 | .75 | .71 | 40 | .65 | .59 |
| PVC | HPGP | 100 | .15 | .13 | 100 | .15 | .15 | 100 | .21 | .19 |
| | WE | 100 | .11 | .11 | 100 | .15 | .15 | 100 | .16 | .16 |
| | FS | 100 | .18 | .18 | 100 | .17 | .17 | 100 | .25 | .25 |
| | GP | 100 | .24 | .23 | 100 | .33 | .33 | 100 | .34 | .33 |
| | BC | 100 | .27 | .27 | 60 | .50 | .50 | 100 | .32 | .32 |
| | LP | 100 | .29 | .29 | 100 | .32 | .32 | 100 | .32 | .31 |
| | TP | 80 | .40 | .40 | 60 | .42 | .42 | 60 | .41 | .41 |
| | Bare | 40 | .74 | .70 | 40 | .55 | .51 | 40 | .55 | .54 |
| Hypalon* | HPGP | 100 | .07 | .07 | 100 | .18 | .18 | 100 | .25 | .25 |
| | WE | 100 | .09 | .09 | 80 | .37 | .32 | 60 | .45 | .45 |
| | FS | 100 | .13 | .13 | 100 | .23 | .21 | 60 | .38 | .38 |
| | GP | 100 | .30 | .24 | 40 | .55 | .48 | 40 | .60 | .60 |
| | BC | 80 | .35 | .30 | 80 | .40 | .40 | 60 | .55 | .55 |
| | LP | 100 | .23 | .20 | 60 | .50 | .48 | 40 | .80 | .65 |
| | TP | 60 | .47 | .47 | 60 | .50 | .50 | 60 | .43 | .43 |
| | Bare | 10 | 2.0 | 1.8 | 20 | 1.4 | 1.2 | 20 | 1.0 | .95 |

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Cable Lubricant Performance

For each of the seven cable lubricants, an average value of the nine measured kinetic coefficients of friction was calculated and used to evaluate performance. The lubricants were ranked from the lowest to highest mean value of the kinetic coefficient of friction.

The ranking of lubricants with the mean value of the static coefficient of friction is identical to the mean kinetic coefficient ranking except for the low shear performance rating of the liquid polymer lubricant. Its ranking would move from second to fourth.

Table III Coefficient of Friction Averages (Inclined Plane Method)

| | STATIC | KINETIC |
|----------------------------|--------|---------|
| 1. Wax Emulsion | 0.277 | 0.249 |
| 2. Liquid Polymer Solution | 0.513 | 0.251 |
| 3. HP Gel Polymer Solution | 0.433 | 0.428 |
| 4. Fluffed soap | 0.478 | 0.466 |
| 5. Talcum Powder | 0.548 | 0.498 |
| 6. Gel Polymer Solution | 0.580 | 0.540 |
| 7. Bentonite Clay | 1.01 | 0.956 |
| Control | 0.854 | 0.603 |

Table IV Coefficient of Friction Averages (Friction table method)

| | STATIC | KINETIC |
|------------------------------------------|--------|---------|
| 1. High Performance Gel Polymer Solution | 0.163 | 0.154 |
| 2. Wax Emulsion | 0.199 | 0.187 |
| 3. Fluffed Soap | 0.212 | 0.207 |
| 4. Gel polymer solution | 0.347 | 0.327 |
| 5. Bentonite Clay | 0.353 | 0.343 |
| 6. Liquid polymer solution | 0.370 | 0.348 |
| 7. Talcum Powder | 0.453 | 0.451 |
| Control | 0.932 | 0.857 |

DISCUSSION OF RESULTS

Table I consists of the coefficients of friction determined by the inclined plane method for the seven different lubricants tested and the control. The values varied greatly from one lubricant type to another. The lower viscosity lubricants (wax emulsion and liquid polymer solution) yielded smaller coefficients of friction than the high viscosity lubricants (gel polymer solution and bentonite clay). The ranking of lubricants under low shear appears in Table III.

Table II consists of the coefficients of friction determined by the friction table method. The values varied greatly from one lubricant to another. The lubricant performance ranking appears in Table IV. The high performance polymer gel was found to yield the greatest friction reduction under high shear and the talcum powder the lowest.

Note that both methods of measurement indicate significant differences in coefficient of friction depending on cable jacket type and conduit type. All lubricants generally result in some reduction of friction over the non-lubricated control except for bentonite clay under low shear.

Comparison of the Two Methods of Measurement

The coefficients of friction measured under high shear are, in general, approximately half of the values obtained under low shear.

The large difference between the values determined by the inclined plane method and the values determined by the friction table method may be attributed to one factor: the difference in magnitude of the normal and pulling forces.

Under low normal loads, less than 75 N/m (5 lbf/ft), such as those experienced between the cable and conduit in the inclined plane test, there existed a relatively thick film (1 to 2 mm) of lubricant between the two surfaces. In the cases where this lubricant film was highly viscous (polymer gels and bentonite clay) there was a substantial force required to overcome the viscous drag [3] and to push a quantity of lubricant ahead of the cable section. This force was very significant relative to the low frictional force, $mg\sin\theta$, exerted by gravity on the cable, and resulted in an artificially high apparent coefficient of friction. The ranking of lubricants under low shear, therefore, is primarily a ranking of lubricant viscosity.

For the friction table method of measurement, the normal force between the two surfaces was relatively high [2920 N/m (200 lbf/ft)] which squeezed the lubricant into a very thin film (1 -10 μm). The pulling force [44 to 147 N (10 to 33 lbf)] required to slide the conduit section under the cable section was much greater than the pulling force required under low normal loads [4.4 to 8.8 N (1 to 2 lbf) for the inclined plane test]. Thus, the additional force required to overcome the viscous drag of the lubricant became a negligible factor, and an accurate coefficient of friction was obtained.

The performance of the lubricants under high shear differed significantly. Some lubricants were able to withstand the high normal pressure and still perform effectively. The high performance gel polymer lubricant proved superior under these conditions.

Correlation for Use in Pulling Equations

Coefficient of friction values determined by the inclined plane test are only applicable to very short, perfectly straight pulls with lightweight cable. Even during these types of pulls, sidewall pressures can exceed 290 N (20 lbf) because of the triplexing of cables, high percent conduit fill, or spiraling tendency of the cable.

When sidewall pressures between cable and conduit surfaces exceeds 290 to 730 N/m (20 - 50 lbf/ft), which includes a majority of pulls that require lubricant, cable lubricant performance is similar to that observed in the friction table method of measurement. Therefore, the coefficients of friction obtained by this method should be better predictors of cable tensions in field installations.

The coefficients of friction in Table II were measured under experimental laboratory conditions with clean cables and conduits. They do not include any adjustment for the forces required to bend cables around corners, the additional forces required to pull cable through sand, dirt or imperfections in the conduit, or the forces required to pull cable through unlubricated sections of conduit.

Actual field cable tensions may correlate best with those calculated using the coefficients of friction measured under high shear when proper cable pulling practices are followed.

1. The cable should be clean.
2. The conduit should be continuous and free of any dirt, sand or obstructions.
3. Lubricant should be spread throughout the conduit run to insure that it is present at all points of cable/conduit contact.

Although a small number of measured cable tensions have shown excellent agreement with the tensions predicted by using the high shear coefficients of friction developed above, it is recommended that future work encompass a large number of actual cable pulls with controlled pulling conditions to more accurately correlate theory and practice.

Due to the large number of variables involved in cable pulling (condition of conduit and cable, quality of lubricant and lubricant application, temperature, etc.) and the limited correlation between theory and practice at the time of publication, it is recommended that the experimentally determined coefficients of friction in Table II be used to calculate a lower limit of the expected tension in actual cable pulls. Specific field conditions and measurements can be used to determine what additional safety factor, if any, is necessary.

CONCLUSION

Coefficients of friction obtained under high shear conditions are shown to be better predictors of the performance of cable lubricants in actual field cable installations into conduits with bends. The measured values indicate the possibility to design longer, more complex duct systems with fewer man-holes/splices and a major reduction in cost.

Actual field tensions may closely approximate predicted tensions if proper pulling and lubricating practices are followed.

REFERENCES

- [1] R.C. Rifenberg, "Pipe Line Design for Pipe Type Feeders", AIEE Power Apparatus and Systems, No. 9, Paper 53-389, December, 1953
- [2] P.A. Tipler, "Physics", New York, Worth Publishers, Inc., pp. 156 - 158, 1976
- [3] R. B. Bird, W. E. Stewart, E. N. Lightfoot, "Transport Phenomena", New York, John Wiley & Sons, Chapter One, 1960