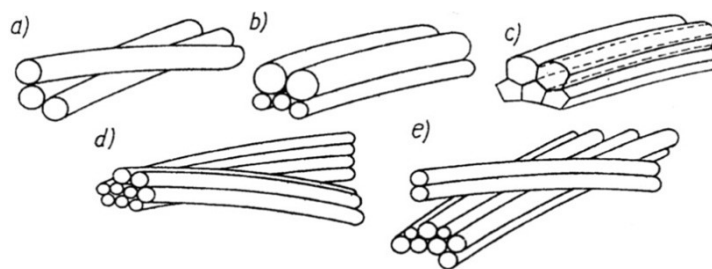


## 6 DETERMINATION OF FRICTIONAL CONTACT COEFFICIENT OF ROPE WITH SURFACE CONTACT OF WIRES AND FRICTIONAL LINING

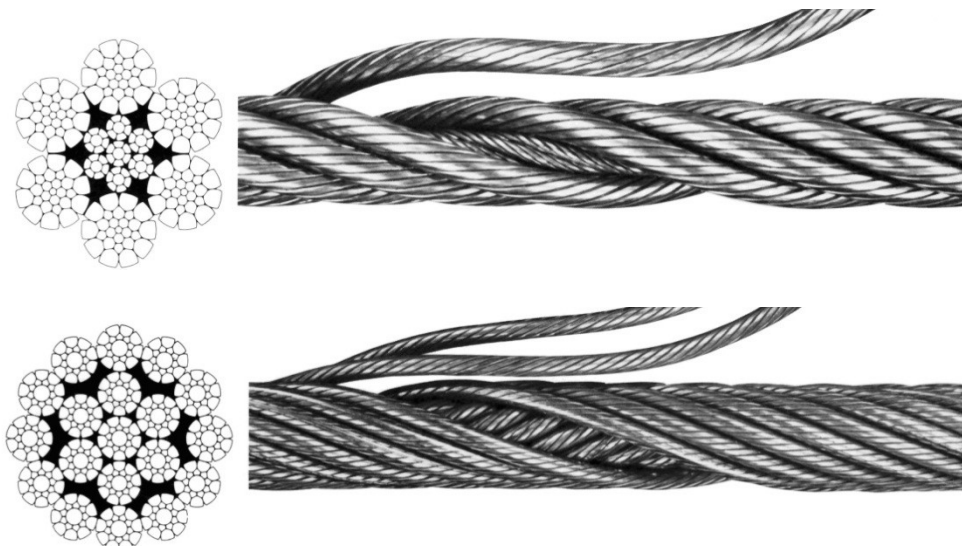
### 6.1 Introduction

A steel rope was applied first time in 1834. Many miscellaneous constructions of steel ropes have been created until now. One of the basic features characterizing steel ropes made of rounded strands, is the type of contact between the wires in strands, which has very significant influence on the durability of a rope. For many years point, linear, or combined point-linear or linear-point contact of wires in a strands (fig. 6.1) [1, 4, 8, 11, 13, 14, 15, 16].



**Fig. 6.1** Kinds of contacts of wires in strands of steel ropes: a) point, b) linear, c) surface, d) point-linear, e) linear-point

Due to the greater durability in about 70% of ropes applied in practice a linear contact of wires was used. In recent years a new construction of rope was developed, in which contact between wires in strands is surface or surface-linear (fig. 6.1c).



**Fig. 6.2** View of compacted ropes' constructions

Surface contact of wires in strands is obtained by cold plastic working of strands with linear contact, depending on radial plastic crushing of strands (forming). First manufacturing

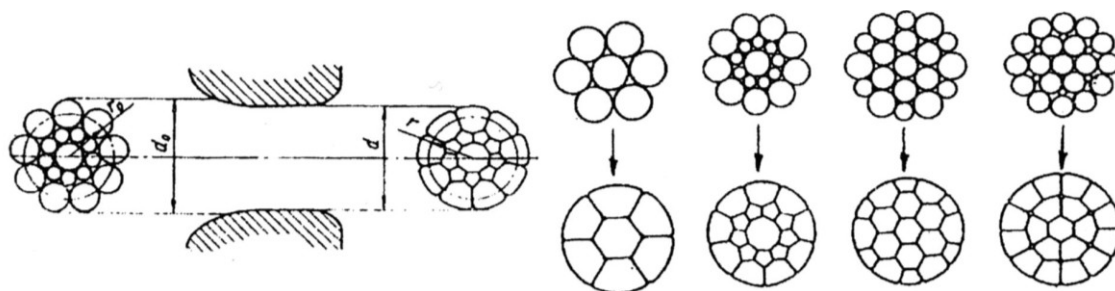
technologies of ropes with surface contact of wires in a strand was developed in Great Britain, and later in Japan. These ropes were applied also in Spain, Germany, Russia, Ukraine, and Czech Republic. Due to their different construction relating to previously used, they were called compacted.

In Poland works on construction of rope with surface contact of wires were carried out since 1968. In 1971 first produced in country compacted rope with diameter of 13 mm, was assembled in ski lift in Szczyrk.

Further works resulted in development of construction of ropes with diameter of 23 and 20 mm, production of which began in 1985, and ropes with diameter of 33 mm in 1992.

In fig. 6.2 views of exemplary constructions of compacted ropes are presented.

Technology of production of ropes with surface contact of wires depends on the radial crushing of strands (fig. 6.3) by their pulling or rolling, what causes permanent plastic deformation of wires, and subsequently coiling of strands into the rope. Plastic deformation of primary rounded wires leads to multiple enhancement of contact's area. Thanks to that, contact stress in the points of contact of wires in strands, between the strands, and in the points of contact between the wires and the bottom of rope pulley's groove, undergo a considerable decrease.



**Fig. 6.3** Way of radial deformation of a strand in a drawing die and cross-sections of various constructions of, compacted strands

Ropes with surface contact of wires in strands characterize with following advantages [2, 3, 5, 6, 7, 9, 10, 16]:

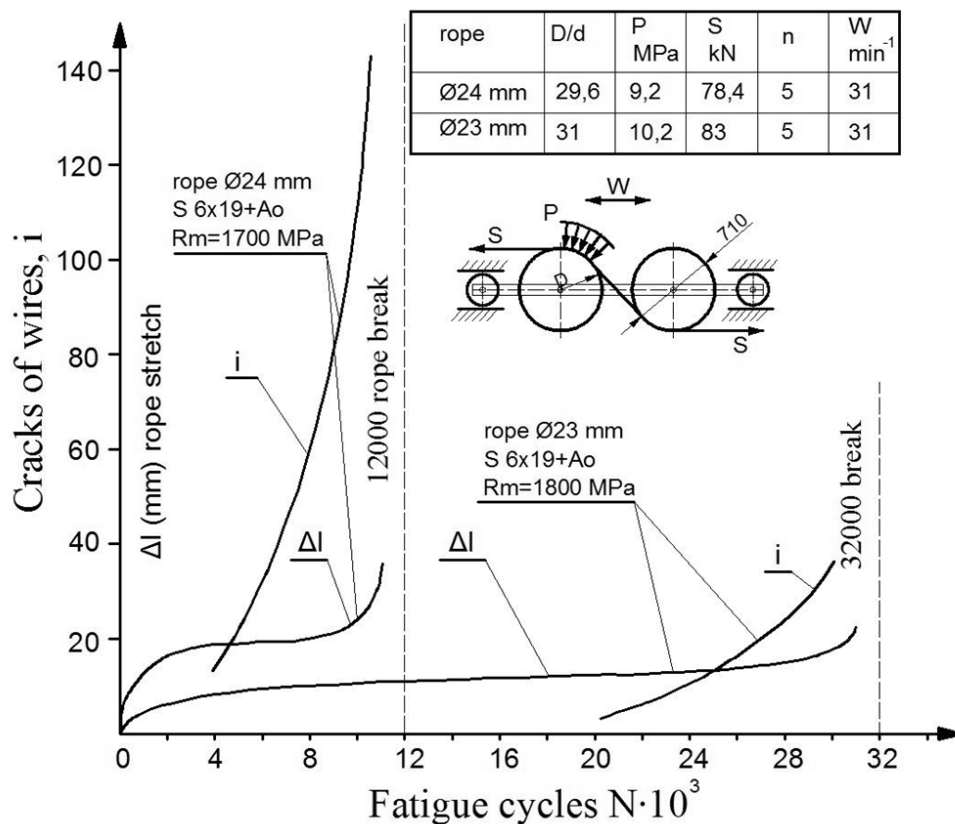
- Greater filling of metallic cross-section of rope at the same diameter of ropes,
- Surface contact of wires contributes to the decrease of contact stresses between the wires, strands, as well as between the rope and groove of rope pulley,
- Application of plastic deformation of strands is also a form of unstressing the ropes,
- More favorable distribution of stresses in wires of rope in its cross-section,
- Greater breaking strength,
- Greater resistance to side thrusts,
- Greater wear and abrasion resistance,
- Lesser turning-off moment,
- Greater young's modulus of rope (smaller elongations),
- Increase of fatigue life from 50÷180% (according to different authors),
- Greater corrosion resistance,
- High uniformity of mechanical properties,

- High flexibility, lower D/d parameter.

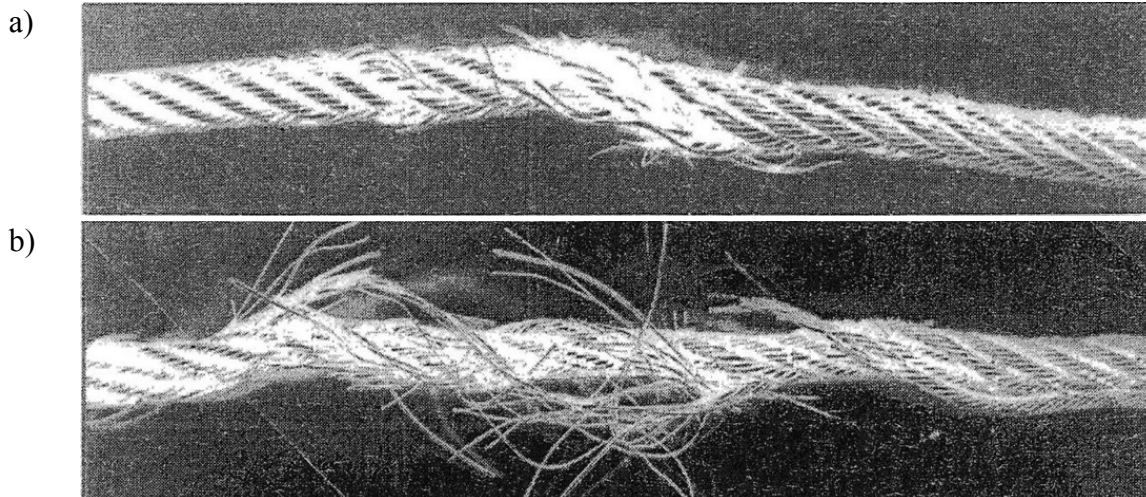
On the superiority of compacted ropes over the ropes with surface contact of wires testify results of fatigue tests, which are one of the most significant strength tests of ropes. Fatigue bending tests were conducted in special double-sided bending fatigue machines.

In fig. 6.4 the results of fatigue tests (mean values from 3 trials) of steel ropes with diameter of 23 mm and surface contact of wires, and with diameter of 24 mm and linear contact of wires are presented [2, 3]. All ropes was unstressed by Tru-Lay method. Ropes of surface contact of wires was additionally unstressed by application of plastic deformation of strands. Obtained values visualize a clear difference in the course of an increase of cracks of wires and elongation of rope's segment, and in the amount of cracks of wire, at which the ropes underwent the damage.

Analyzing obtained results it can be stated, that compacted ropes was resisting a 166% more fatigue cycles comparing to ropes with linear contact of wires. Ropes with linear contact of wires underwent damages after 12000 fatigue cycles with about 40 visible cracks of wires at the bended segment, and compacted ropes underwent damage after 32000 fatigue cycles with about 30 cracks of wires at the same length of the bended segment. Visual inspections of ropes' segments after fatigue tests resulted, that in a case of ropes with linear contact of wires, cracks were distributed on the almost whole bended segment, whereas in a case of ropes with surface contact of wires, visible cracks of wires were distributed on the much shorten segment at cracks of wires also inside the rope (fig. 6.5).

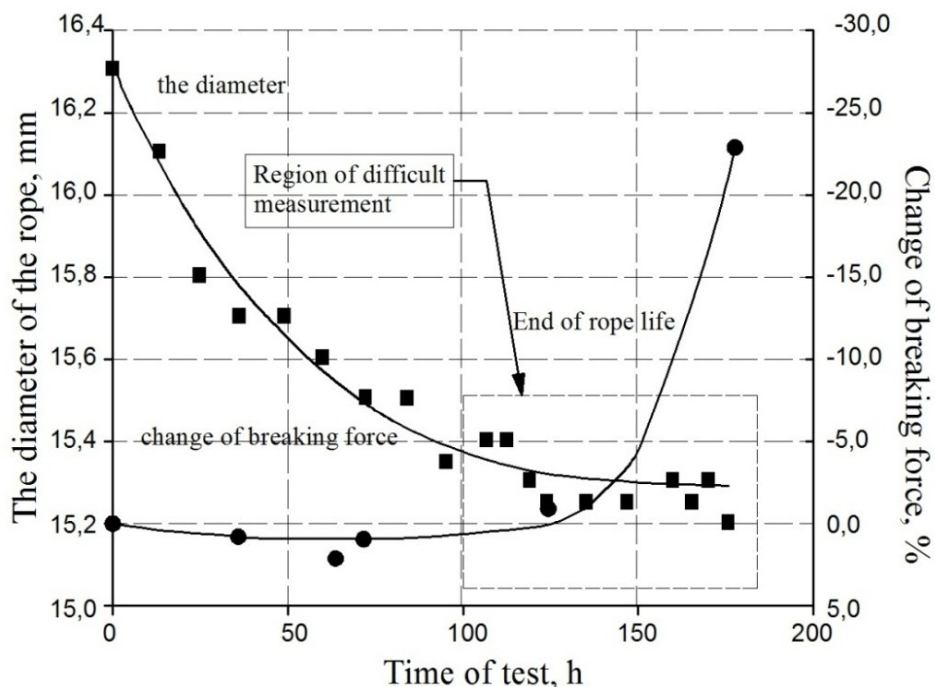


**Fig. 6.4 Results of double-sided bending fatigue tests of steel ropes with linear contact of wires with Ø24 mm and surface contact of wires with Ø23 mm [2, 3]**



**Fig. 6.5 View after fatigue tests of: a) compacted rope b) standard rope**

Next stage of development of compacted ropes was working out the construction of rope with compacted strands [17], which have found application in underground suspended cableways. Before the application comprehensive tests of their durability in specially constructed test stand in DMT (Deutsche Montan Technologie). On the basis of obtained results it was stated, that rope with compacted strands reached about 2.5 times greater durability than the rope compacted totally. Determination of state of rope until its putting away on the basis of change in its diameter and the change in value of breaking force is presented in a fig. 6.6.



**Fig. 6.6 The change of real breaking force and loss in diameter of rope during the tests [17]**

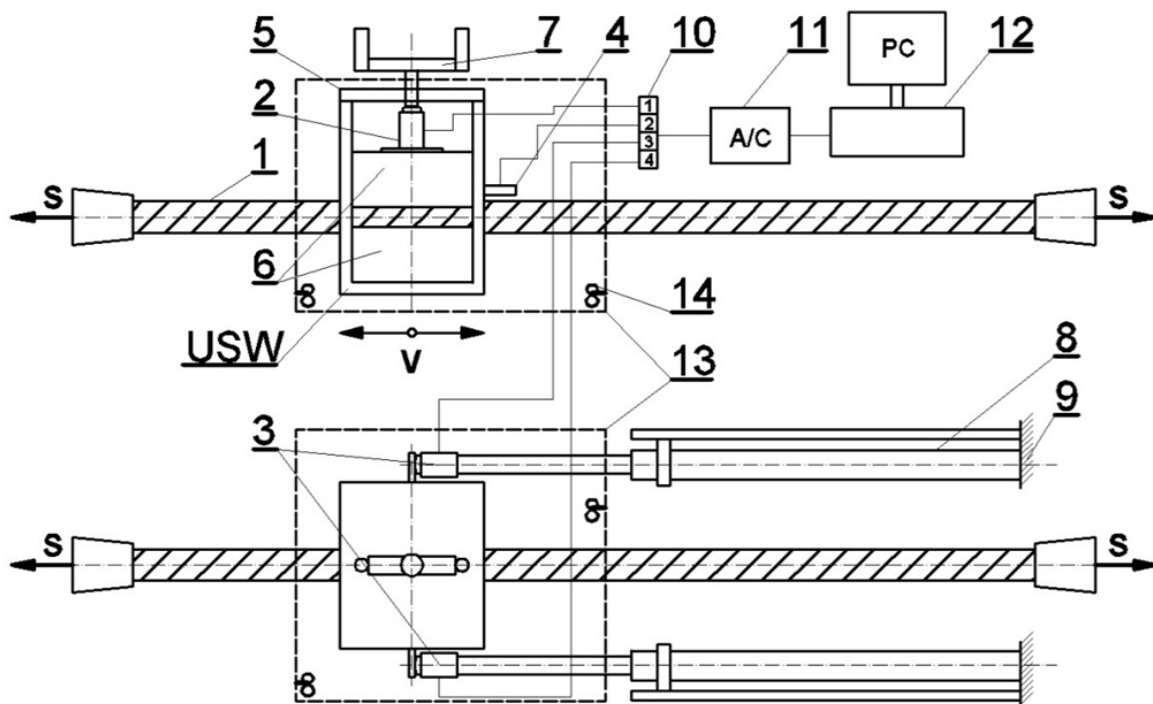
Obtained values were admitted as satisfactory, especially due to great durability of rope. Relatively large decrease of force breaking the rope at little decrease of rope's diameter was also noted.

Presented advantages of compacted ropes (totally, as well as with compacted strands), confirmed results of tests, and also their operation so far, contribute to wider application of these ropes in ropeway installations for vertical transport home and abroad, and in horizontal transport in underground rail-cable cars.

## 6.2 Testing methodology

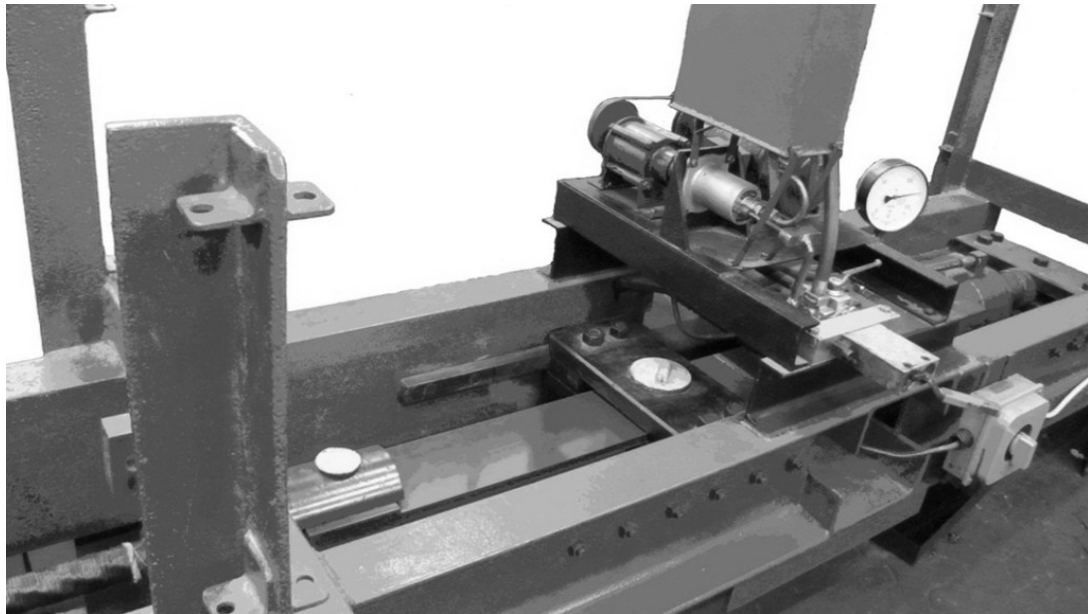
Experimental tests of frictional contact coefficient between the rope and lining (kinetic friction coefficient) was carried out in the Department of Transport and Tribotechnique, Institute of Mining Mechanization, Silesian University of Technology on the stand for determination the friction between the steel rope and lining [2, 3].

In fig. 6.7 the scheme of test stand and register-measuring system is presented. The stand consists of: strain gauge (2) for measuring the pressure force, strain gauges (3) for measuring the friction force, temperature sensor (4), device pressing the blocks of USW lining (5), clamps with lining (6), screw gear (7), hydraulic cylinders (8), casing of testing machine (9), clamps panel (10), A/C card (11), and computer (12). In the stand there can be also distinguished USW lining pressing device, heating chamber (13), and heater (14).

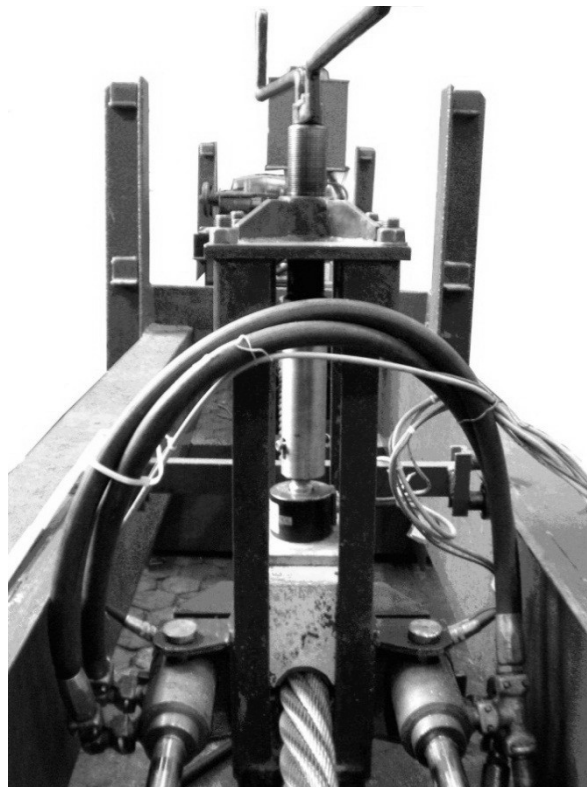


**Fig. 6.7 Scheme of test stand and register-measuring system**

View of tensile testing machine's drive together with connector of rope segment's attachment is presented in fig. 6.8, and view of USW head in fig. 6.9.

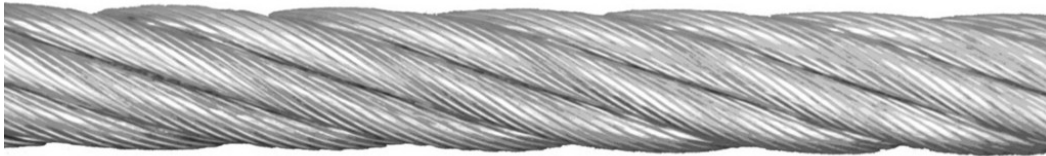


*Fig. 6.8 View of tensile testing machine's drive together with connector of rope segment's attachment*

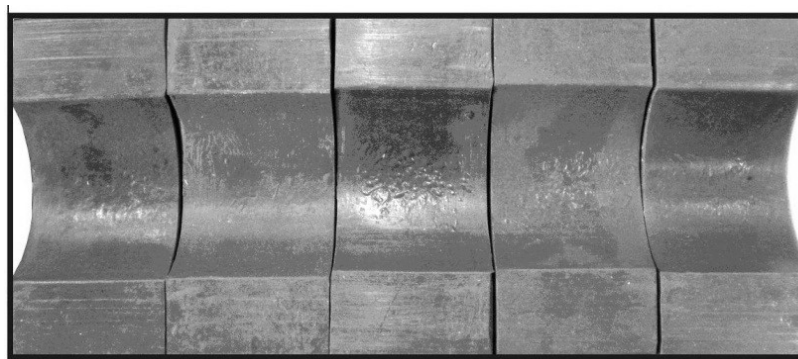


*Fig. 6.9 View of USW head*

For tests the friction pair, consisting of steel compacted right-hand Lang's laid rope with nominal diameter of 47 mm (real 50 mm), manufactured by Teufelberger Seil GmbH (fig. 6.10) and Modar R3/Mz lining. View of block consisting of five elements of lining is presented in fig. 6.11.



**Fig. 6.10** Hoisting compacted right-hand Lang's laid rope of 6xK41WS+FC type manufactured by Teufelberger Seil GmbH

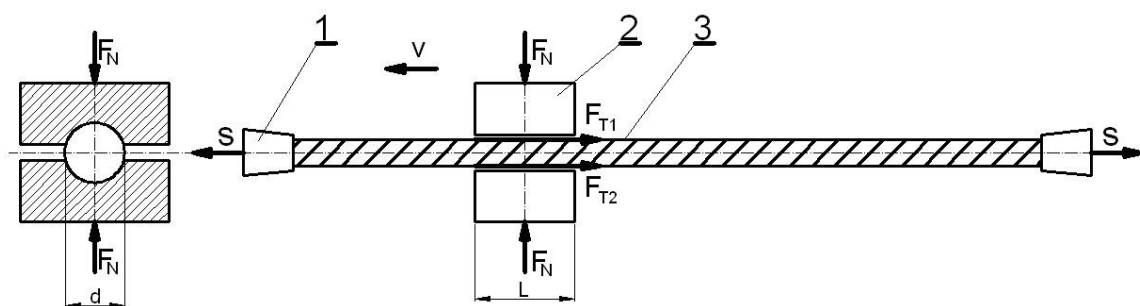


**Fig. 6.11** View of friction lining block applied in stand tests

Tests were carried out for four states of rope–lining friction pair:

- Dry friction pair,
- Wet friction pair,
- Lubricated friction pair,
- Lubricated friction pair + water.

Tests of surface lubricated rope were conducted after 4 and 6 hours from its lubrication. During the tests of dry friction pair the rope and lining were dry, without the grease. Tests were carried out at ambient temperature in the laboratory ( $19^{\circ}\text{C} \div 21^{\circ}\text{C}$ ) and at ambient temperature  $30^{\circ}\text{C}$  (in heating chamber), and relative humidity of air in laboratory amounted to  $46\% \div 55\%$ . Measurements were repeated sixfold (according to the standard the first measurement was refused and to further calculations next five measurements were taking into account) [12].



**Fig. 6.12** Cooperation model of line and lining assumed for laboratory tests:  
1 - conical sleeves, 2 - lining, 3 - rope

During each of trial the measuring system was registering instantaneous values of: friction force, pressing force of rope to samples of friction lining, temperature of rope's surrounding, and time of conducted tests with frequency of 20 Hz. Tests were carried out according to German standard DIN 21258. Cooperation model of rope and lining used to determine the kinetic friction coefficient is presented in fig. 6.12.

Calculations of average value of kinetic friction coefficient, for single test, were done basing on the instantaneous values of kinetic friction force  $F_{T1}$  and  $F_{T2}$ , and values of pressing force of steel rope to lining  $F_N$  registered by the measuring system (fig. 6.12).

According to the presented scheme the kinetic friction coefficient between rope and lining is calculated from the dependence:

$$\bar{\mu}_k = \frac{\bar{F}_T}{F_N} \quad (6.1)$$

where:  $F_N$  – pressing force of steel line to lining, N,  
 $\bar{F}_T$  – average kinetic friction force, N.

Average value of kinetic friction force, for single test, was calculated from the dependence:

$$\bar{F}_T = \frac{\int_{t_1}^{t_2-t_1} F_{T1}(t)dt + \int_{t_1}^{t_2-t_1} F_{T2}(t)dt}{2(t_2 - t_1)} \quad (6.2)$$

where:  $t_2-t_1$  – time interval of test, s,  
 $F_{T1}(t)$  – friction force in a function of braking time, N,  
 $F_{T2}(t)$  – friction force in a function of braking time, N.

According to requirements of the standard [12] each measurement has to be repeated six-fold and as the final value the average value of friction coefficient  $\bar{\mu}_s$  from five measurements should be taken.

Pressure of rope on the lining was calculated from the dependence:

$$p = \frac{F_N}{A} = \frac{F_N}{L \cdot d}, \text{ MPa} \quad (6.3)$$

where:  $F_N$  – force pressing clamps with the linings,  
 $L$  – length of lining block in one clamp,  
 $d$  – measured diameter of rope,  $d = 50$  mm.

Dependence between pressing force of lining and instantaneous friction force was determined from the equation:

$$F_T = k \cdot \mu \cdot F_N, \text{ N} \quad (6.4)$$

where:  $F_T$  – average friction force,  
 $F_N$  – pressing force of lining,  
 $\mu$  – friction coefficient,  
 $k$  – number of contact surfaces.

Kinetic friction coefficient was determined from the dependence:

$$\bar{\mu}_k = \frac{\bar{F}_T}{F_N} \quad (6.5)$$



where:  $\bar{F}_T$  – calculated average friction force during a slip,  
 $F_N$  – measured pressing force of rope on the lining. During the computer tests the system of data acquisition registers in real time the pressing force  $F_N$  with the use of legalized strain gauge, and friction force  $\bar{F}_T$  with the use of strain gauges attached on the piston rods of cylinders.

The average value (from series of trial) of kinetic friction coefficient is calculated from the dependence:

$$\bar{\mu}_{sr} = \frac{1}{n-1} \sum_{i=1}^n \bar{\mu}_k \quad (6.6)$$

where: n – number of repeats of given test.

### 6.3 Results

Tests were carried out for two value of pressing force of lining on the rope. In tab. 6.1 there are listed results of tests of values of kinetic friction coefficient for pressure  $p = 2$  MPa, whereas in tab. 6.2 for pressure  $p = 2.4$  MPa.

**Tab. 6.1 Values of kinetic friction coefficient for pressure  $p = 2$  MPa**

|                                                                                    | Number of measurements |       |       |       |       | $\bar{\mu}_{sr}$ |
|------------------------------------------------------------------------------------|------------------------|-------|-------|-------|-------|------------------|
|                                                                                    | 1                      | 2     | 3     | 4     | 5     |                  |
| <b>Dry lining and rope</b>                                                         |                        |       |       |       |       |                  |
|                                                                                    | 0,571                  | 0,565 | 0,553 | 0,569 | 0,561 | 0,564            |
| Relative humidity                                                                  | 52%                    |       |       |       |       |                  |
| <b>Lina i wykladzina mokra</b>                                                     |                        |       |       |       |       |                  |
|                                                                                    | 0,573                  | 0,576 | 0,574 | 0,571 | 0,577 | 0,574            |
| Relative humidity                                                                  | 54%                    |       |       |       |       |                  |
| <b>Rope lubricated with Nyrosten N113FS grease, temperature 19°÷21°C</b>           |                        |       |       |       |       |                  |
|                                                                                    | 0,334                  | 0,324 | 0,332 | 0,319 | 0,327 | 0,327            |
| Relative humidity                                                                  | 51%                    |       |       |       |       |                  |
| <b>Rope lubricated with Nyrosten N113FS grease, temperature 30°C</b>               |                        |       |       |       |       |                  |
|                                                                                    | 0,293                  | 0,291 | 0,279 | 0,292 | 0,287 | 0,288            |
| Relative humidity                                                                  | 50%                    |       |       |       |       |                  |
| <b>* Rope lubricated with Nyrosten N113FS grease, temperature 19°÷21°C</b>         |                        |       |       |       |       |                  |
|                                                                                    | 0,419                  | 0,422 | 0,431 | 0,413 | 0,412 | 0,419            |
| Relative humidity                                                                  | 46%                    |       |       |       |       |                  |
| <b>* Rope lubricated with Nyrosten N113FS grease, temperature 30°C</b>             |                        |       |       |       |       |                  |
|                                                                                    | 0,373                  | 0,367 | 0,362 | 0,374 | 0,361 | 0,367            |
| Relative humidity                                                                  | 48%                    |       |       |       |       |                  |
| <b>Rope lubricated with Nyrosten N113FS grease + water, temperature 19°÷21°C</b>   |                        |       |       |       |       |                  |
|                                                                                    | 0,270                  | 0,288 | 0,278 | 0,291 | 0,286 | 0,283            |
| Relative humidity                                                                  | 55%                    |       |       |       |       |                  |
| <b>* Rope lubricated with Nyrosten N113FS grease + water, temperature 19°÷21°C</b> |                        |       |       |       |       |                  |
|                                                                                    | 0,348                  | 0,351 | 0,363 | 0,356 | 0,362 | 0,356            |
| Relative humidity                                                                  | 53%                    |       |       |       |       |                  |

Tab. 6.2 Values of kinetic friction coefficient for pressure  $p = 2,4 \text{ MPa}$ 

|                                                                      | Number of measurements |       |       |       |       | $\bar{\mu}_{sr}$ |
|----------------------------------------------------------------------|------------------------|-------|-------|-------|-------|------------------|
|                                                                      | 1                      | 2     | 3     | 4     | 5     |                  |
| <b>Rope lubricated with Nyrosten N113FS grease, temperature 30°C</b> |                        |       |       |       |       |                  |
|                                                                      | 0,269                  | 0,266 | 0,271 | 0,258 | 0,262 | 0,265            |
| Relative humidity                                                    | 42%                    |       |       |       |       |                  |
| <b>Rope lubricated with Nyrosten N113FS grease, temperature 30°C</b> |                        |       |       |       |       |                  |
|                                                                      | 0,337                  | 0,336 | 0,334 | 0,328 | 0,331 | 0,333            |
| Relative humidity                                                    | 44%                    |       |       |       |       |                  |

#### 6.4 Summary

Ropes with surface contact of wires (compacted), presented in the paper, have many advantages relating to ropes with linear contact of wires used so far. Results of tests, and conclusions resulting from previous operation of these ropes in ropeway installations of horizontal and vertical transport in various branches of industry, show their great usefulness and high durability.

More favorable distribution of stresses in rope's wires, greater breaking strength, increased resistance to abrasion and corrosion, and first of all a high fatigue life cause, that these ropes should find wide application in mining. First cases of application of these ropes in auxiliary transport facilities in domestic coal mines, and in winding plant in Rozbark Coal Mine, confirmed all advantages of compacted ropes.

Although compacted ropes are applied since several years, still they require investigations, which should include fatigue tests of ropes and rope-lining frictional contact coefficient. Tests of kinetic friction coefficient of friction pair compacted rope-lining, carried out in Institute of Mining Mechanization, proved that in a case of compacted ropes, values of this coefficient are much more favorable, than in a case of other types of ropes. In order to generalize the conclusions resulting from these tests, it is necessary to carry out further investigation for greater number of diameters of these ropes and for different pressing forces.

Assuming that compacted ropes will be more often applied in practice, it becomes also necessary to develop separated conditions of assessment of technical state of these ropes, and particularly the criteria of their wear. There seem necessary also further fatigue tests of ropes with surface contact of wires with great diameters.

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