TALLINNA TEHNIKAÜLIKOOL
MEHAANIKATEADUSKOND

TTÜ materjalitehnika instituut
Metallide tehnoloogia õppetool

MTT70LT

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Kaetud keskpinge õhuliini juhtmete triboloogiline uuring

Autor taotleb
tehnikateaduse magistri
akadeemilist kraadi

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TALLINNA TEHNIKAÜLIKOOL
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Tribological study of covered medium voltage overhead lines conductors

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EESSÕNA

Lõputöö teema «Kaetud keskpinge õhuliini juhtmete triboloogiline uuring» pakus välja minu juhendaja Maksim Antonov. Teema tundus huvitav, sest mind ootasid ees mitmed huvitavad ülesanded: võimalus tutvuda uue masinaga «Block-on-Ring», viia läbi rida katseid laboris ning tänu sellele leida kõige kõrgema kulumiskindlusega kaabel (kest). Lisaks oli võimalus uurida erinevate plastikust kestade käitumist hõõrdumisel puidu ja metalliga. Käesoleva töö juhendamise eest soovin avaldada tänu Maksim Antonovile.

1 INTRODUCTION

Estonia is a country, a larger area of which is covered with forests. Also there are overhead lines that are more than 61000 km long [1].

Covered medium voltage overhead lines conductors (power cables) have a considerable and sometimes even crucial role. The creation of balanced and steady power network system provides an opportunity for improving and controlling economy. Therefore uninterruptable operation of electric power grids is very critical.

In everyday life we used to face such phenomenon as "wear". The wear is observed in all spheres of our life: cycling, where not only tires but also all driving parts of the bicycle are subject to wear; walking that causes wear of sole, joints, cloth etc.

Tribology (it derives from the Greek word "tribos" and means friction) is a science that deals with the wear. Tribology studies contract interaction of solid bodies that takes place upon their relative movement. It covers a range of friction, wear and lubrication issues [2].

In order to determine the degree of resistance of cable sheath to abrasive wear upon its friction of the wood it is necessary to carry out tests under conditions that are maximally close to natural conditions. For this purpose Department of Materials Engineering uses Block-On-Ring testing device.

The purpose of this thesis is to develop the process of testing covered medium voltage overhead lines conductors (cable sheath) for wear, study of different parameters of the device such as test duration, test type and test load. The results of this work will help to develop the procedure for wear testing of cable sheaths and also to use cable sheaths with higher wear-proof level for covered medium voltage overhead lines conductors in future.

2 CABLES, TYPES, PROPERTIES, SCOPE OF USE

In terms of functions cable are divided into two main groups: power cables and control cables. Power cables are used for transmitting and distributing power energy. They transfer electric power to different current collectors and switchgears. Control cables are necessary for connecting electric devices, hardware and terminal blocks (for example, control, automation and alarm networks) with power source [3].

2.1 Power cables

Power cables transmit electric power to power plants. They have one or several insulated conductors, enclosed into metal or non-metal sheath that can be covered with special protective layer or armour, depending on routing and operation conditions [4].

Power cables consist of the following main elements: power conductors, insulation, sheath and protective coats. In spite of main elements power cables may include screens, neutral conductors, protective earthing conductors and fillers (see Figure 1) [4].

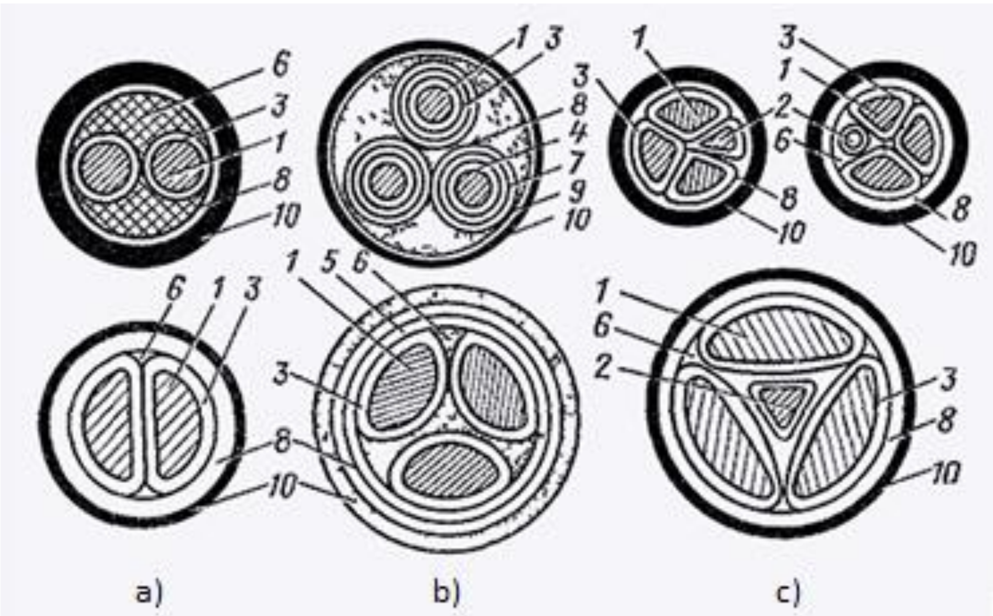


Figure 1. Power cable cross section [4]

In the Figure 1 following symbols are used:

a) Double-conductor power cables with circular or segmental conductors;
b) Three-conductor power cables with wrapping and separate sheaths;
c) Four-conductor power cables with neutral conductor of sectoral, circular and triangle shape

1. Electrical conductor
2. Neutral conductor
3. Conductor insulation
4. Conductor screen
5. Wrapping
6. Filler
7. Insulation screen
8. Sheath
9. Armour
10. Outer sheath

Electrical conductors are designed for passing of electrical current. They may be main or neutral. Main conductors are used for performance of the main function of cable, i.e. electrical power transmission [4].

Neutral conductors are designed for phase current difference (positive sides) in case of uneven loading. They are connected to power source neutral conductor [4].

Protective earthing conductors provide the bonding connection between all exposed and extraneous conductive parts of an installation, to create the main equipotential bonding system. These conductors conduct fault current due to insulation failure (between a phase conductor and an exposed conductive part) to the earthed neutral of the source [5].

The insulation ensures necessary electrical strength of conductor against each other and earthed sheath (ground) [4].

The screens protect external loops against the effect of electromagnetic fields of currents, passing through power cable, and ensure symmetry of electrical field around cable conductors [4].

Wrapping provides a barrier between layers, e.g. to prevent any sticking during extrusion [6].

Fillers eliminate free spaces between structural elements of power cable for the purpose of sealing, shaping and ensuring mechanical resistance of cable structure [4].

Sheaths are used for protection of conductor insulation against sun light, moisture, different chemical substances and also its protection against mechanical damages [4].

Armour is used for mechanical protection of the conductor. Cables with armour can be buried directly and used in external or underground projects. The armouring is normally connected to earth and can sometimes be used as the earth conductor for the equipment supplied by cable. Typically is used steel wire armour or aluminium wire armour. Tinning or galvanising is used for rust prevention. Phosphor bronze or tinned copper braid is also used when steel armour is not allowed [7].

2.2 Scope of use of power cables

Power cables are designed for distribution of electrical power in lighting and power plants when their use is more technically and economically feasible than the use of wire.

2.3 Main types of cable sheath

In order to prevent penetration of moisture, different chemical substances into the insulation and also protect it from mechanical damages the cable is fitted with protective sheath.

Cable sheath may consist of one or more sealing and reinforcing layers. Different materials, such as tissue, plastics, metals and rubber, can be used as these layers.

2.3.1 Metal sheaths by GOST 1841-73

Metal sheaths are used for high-voltage cables, for example ААБл, АСБ (GOST 18410-73) - aluminum and lead sheathes, respectively.

ААБл cable is a power cable with impregnated paper insulation for low voltage. AABl cable is used for power transmission and distribution in the stationary equipment and max 10 kV AC 50 Hz electric networks, or in DC electric networks [4].

АСБ cable is a power cable with aluminum wire, in paper insulation impregnated with a special viscous composition, in the lead sheath. The sheath made of the molded lead tube protects the live strands from crushing, abrasion etc. In order to prevent the lead corrosion under the influence of an aggressive environment, the cable sheath is covered with a layer of bitumen, polyethylene terephthalate tapes, and paper. АСБ cable is designed for power transmission and distribution in stationary equipment in max 10 kV 50 Hz electric networks [4].

The lead is used due to that fact that it is easy to process it. It is soft metal with low melting point. Moreover it is characterized by excellent flexibility and the resistance to aggressive substances. This material is well soldered in field conditions upon mounting of cable line. However, vibration and heat loads cause cracks. Since the lead has high creep flow large slopes of cable line may cause irrevocable stretching of cable sheath that, in its turn, may result in cable breaking [8].

Aluminum sheaths have higher strength than lead sheaths by 2.0 - 2.5 times. They are lighter and resistant to vibration loads. In some cases this material may be used instead of cable armor. Moreover this sheath can be used as a screen while having excellent electrical conductivity. The disadvantage of this sheath is that it has low resistance to electrochemical and solid corrosion and it is rather expensive [8].

Advantages of metal sheaths [8]:

- High workability
- Control of properties though use of different additives
- Concurrent screening of conductors

Disadvantages of metal sheaths [8]:

- Anticorrosion protection is required
- Expensive metals
- The lead is very flexible and may lose its initial shape

2.3.2 PVC sheaths

Polyvinylchloride compound, used in cable industry, is a mixture of PVC resin (polyvinyl chloride), obtained by polymerization of vinyl chloride (CH_2=CHCl) with plasticizers, stabilizers, fillers and other components [8].

In terms of features and requirements polyvinyl chloride compounds that are widely used in cable industry can be divided into three groups (see Figure 2).

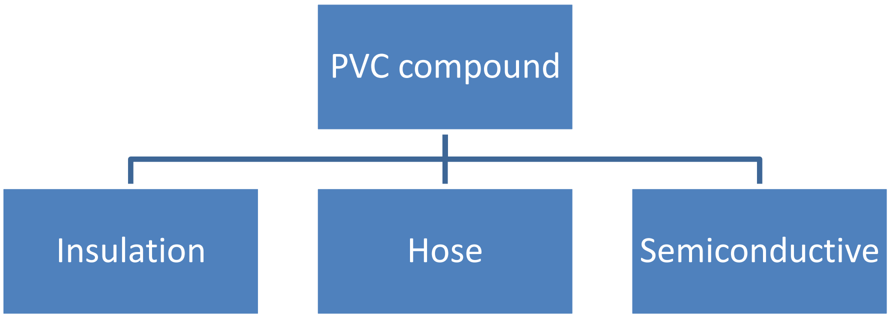


Figure 2. Types of PVC compounds

Insulation PVC compounds are characterized by high electrical characteristics within wide temperature range.

Hose PVC compounds protect main structural elements of cable against the effect of external environment.

Semi conductive PVC compounds takes an intermediate places between dielectric and conductor in terms of their electrical characteristics.

Cable sheathing PVC compounds, used for sheath has the composition that differs from that of Insulation PVC compounds. Polymer requires protection against light ageing, it has high mechanical strength and the resistance against oil and gasoline. Moreover, polymer could be used at low temperatures [8].

Evaporation of plasticizer reduces characteristics of polymer during of operation.

Advantage of PVC sheath [8]:

- Low costs
- The resistance to chemical compounds
- Sufficient mechanical strength
- Air-tightness

Disadvantages of PVC sheath [8]:

- Low flexibility (in comparison with rubber)
- Large mechanical loads are unacceptable

2.3.3 Rubber sheaths

Rubber sheaths have high mechanical resistance to stretching, impact and torque loads. They also protect conductor insulation against sun radiation and other atmospheric effects.

There are several types of rubber sheath (the diversity is determined by applications): sheath for severe, medium and light operation conditions, oil-proof sheaths, sheaths for low temperatures and fire-resistance sheaths [8].

Sheaths from natural rubber with reasonably selected soot, used as filler, has breaking point and tensile strain at break that is 2 times higher than that of styrene-butadiene-rubber. However the resistance of styrene-butadiene-rubber to ageing, light and weather is considerably higher in comparison with natural rubber. Chloroprene rubber is characterized by high ozone, light and weather resistance in comparison with natural rubber and styrene-butadiene-rubber. Chloroprene rubbers also have excellent oil resistance and do not continuation inflammation in case of removing of the cables away from the source of fire [8].

Long-term acceptable working temperature of chloroprene rubber is by 10 ºC higher than that of natural rubber and styrene-butadiene-rubber. This rubber withstands the temperature of up to 260 ºC within 4 hours [8].

Advantages of rubber sheaths [8]:

- Excellent flexibility
- Moderate cost of synthetic rubber
- Excellent air-tightness

Disadvantages of rubber sheaths [8]:

- Sensitivity to simultaneous effect of light radiation and oxygen with further destruction of the surface
- Low resistance to chemical compounds

3 FRICTION AND WEAR

Surrounding world moves continuously. Mechanical movement is a type of this movement. It comprises movement of one bodies against the another ones. All mechanical movements provide for contact of objects between each other with liquid or gaseous medium, for example with water or air [9].

3.1 Friction

The friction is a resistance that arises between two bodies pressed against each other upon their relative movement along contact surface. The resistance force directed to the side that is opposite to movement direction, is called friction force. As well as any force this force depends on configuration at microscopic rather than macroscopic change of bodies', localized in surface layers. The friction force is divided into the following types in terms of amount of movement, depending on its load: dynamic friction force, incomplete static friction force and complete static friction force that is usually called simple static friction force [10].

Dynamic friction force corresponds to very long inconvertible relative movements, the value of which depends on applied force [10].

Incomplete static friction force corresponds to very slow, partially convertible movements with value that which is proportional to applied force [11].

Complete static friction force corresponds to maximum value of preliminary displacement that which preliminary displacement transits into relative displacement [12].

As it is shown on Figure 3 friction can be divided into three types on the basis of kinetic values:

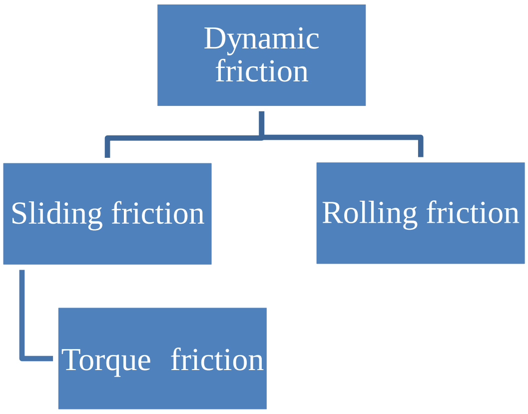


Figure 3. Friction types

Sliding friction one and the same nominal surface of one body gradually moves along the surface of the other body [12].

Torque friction points, located on the contact surface of two bodies, circumscribe concentric surfaces around the center on spinning axes. Torque friction is one of the types of sliding friction [12].

Rolling friction the body moves along the other body under the effect of movement of force. The vector of the second body coincides with contact surface. Elements of nominal surface, located in tandem, contact with such surface. It is not frequent that one type of friction is accompanied by the other type, for example rolling friction with slipping [12].

The value that characterizes friction surfaces is called friction coefficient and designated by Latin letter "k" or Greek letter "μ" It depends of quality and parameters of fiction surface finishing. Moreover, friction coefficient depends on the speed. As a rule, this dependency is mild and if high measurement accuracy is not required, k value may be considered as constant value. At the first approximation the value of sliding friction force can be calculated by the Equation 1 [12].

$$F = k \cdot N, \tag{1}$$

Where k is a sliding friction coefficient,

N is a normal supporting force.

3.2 Wear

The process of gradual change of body sizes upon friction that is represented by separation of material from the surface or (and) its residual deformation is called wear process. The results of wearing are wear and tear is, expressed in determined units (length, volume and weight) [16].

The ratio rate between part wear rate and sliding distance or scope of performed work is called wear intensity. Wear rate could also be expressed as a ratio between part wear and the time, within which wear takes place. Wear resistance is measured on the basis of the value that is inversely related to wear intensity and rate [16].

3.3 Reasons and purposes of the wear studies

High wear rate leads to unequal stress distribution of working space of the machine, violates normal lubrication mode and results in loss of kinematic accuracy of the mechanism. Wear of the tools and working bodies of the machine results in increase of energy consumption and is accompanied with a reduction of performance rate [14].

Wear and damaging of surfaces reduce endurance strength of parts and may cause their damage even in case of insignificant stress raisers and low nominal voltage. High wear rate has an effects on normal interaction between parts in assemblies, causes additional loads, impacts in joints and vibrations. It may be a cause of unexpected destruction [14].

The study of surface properties of solid bodies that change under friction forces and environment is the most significant field of science. The study of the properties of solid body surfaces allows understand kinetics of physical and mechanical property change and also external and structural parameters [15].

3.4 Wear types

There are three wear stages: interaction of surfaces, changes in surface layers and surface damage. All these stages are interrelated between each other [16].

Surface interaction can be mechanical or molecular (Figure 4). Mechanical interaction causes intrusion and engagement of irregularities. Relative movement of the surfaces results in plastic and elastic edging of the material by intruded surfaces (Figure 4.a). Surface engagement results in their mutual deformation and in extreme cases softer surface can be event cut (Figure 4.b). Molecular interaction is manifested in the adhesion of films covering the contact surfaces (Figure 4.c). In some cases the strength of adhesive bond is so high that its break results in tearing of the material (Figure 4.d) [16].

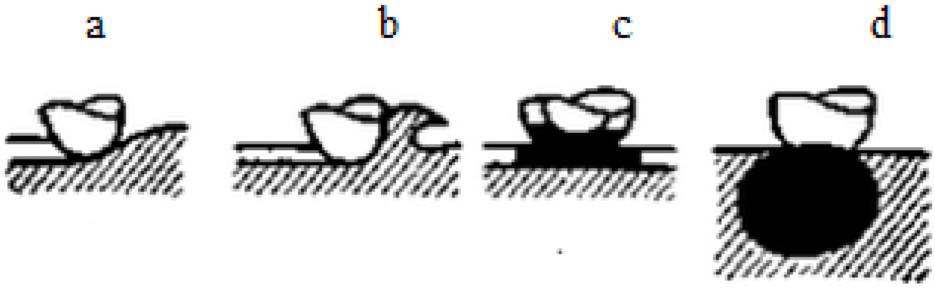


Figure 4. Mechanical and molecular interaction of surfaces that give rise to wear: a) intrusion of irregularities; b) engagement of irregularities; c) adhesion of surface films; d) adhesion [16]

Changes in surface layers take place under the effect of mechanical stresses, temperature and chemical reactions. Above-listed mechanisms and other effects are the basic stages of wear. However, a great number of these mechanisms and their interaction prevent wearing processes from distinct classification. Friction interaction always takes place in definite medium that has considerable effect on tribological processes. These reactions change deformation speed and strength of adhesive bonds under these conditions the adhesion and deformation is still critical. These events are applied for wear type classification [16].

In accordance with GOST 27674-88 there are the following types of machine wear [14]:

- Mechanical wear is a wear, caused by mechanical effects. These types of wear are divided into abrasive, hydro abrasive (gas abrasion), hydro erosive (hydraulic erosion), cavitation, fatigue and fretting wear.

- Abrasive wear is a process of micro deformations and cutting of metal by solid abrasive particles that are located between friction surfaces and also due to direct contact with abrasive medium.

- Hydro abrasive (gas abrasion) wear is a result of the effect of solid particles that are suspended in liquid (gas) and move against part surface.
  The intensity depends on the angle of attack of particles:

$$J = a \cdot V^{m}, \tag{2}$$

  Where *a* is a coefficient that depends on material and angle of attack,

  m is undimensioned power exponent that depends only on material (for steel 3 *m* = 2.3; for steel 45 *m* = 2.5; for cast iron *m* = 2.8; for basalt *m* = 2.5),

  V is velocity.

- Hydro erosive (hydraulic erosion) wear is an erosive wear due to the effect (friction) of fluid (gas) flow on the metal [14].

- Fatigue wear is mechanical wear due to fatigue wear at repeated deformation of micro volume of surface layer material. The effect of repeated fluctuating loads that exceed yield strength results in fatigue peeling and chipping of metal particles [14].

- Cavitating wear is a mechanical wear upon movement of solid body against fluid where gas bubbles burst near the surface. This fact results in high local pressure or temperature that causes surface damage [14].

- Fretting wear takes place in contacting surfaces at small relative displacement of bodies [14].

- Corrosion and mechanical wear due to mechanical effect, accompanied by chemical and (or) electrical interaction of material with medium [14].

- Fretting corrosion wear takes place upon sliding friction with very small oscillatory relative displacements. As a result, pronounced destruction at contact places of working surfaces [14].

3.5 Wear measurement methods

Wear rate is measured by different methods that are based on requirement to minimum time expenditure and possibility for capture of wear for a short time period. For example, micrometer method is based on measurement of wear with use of micrometers, indicators and other tools for measurement of linear wear. The benefits of this method: simplicity, accessibility and the possibility for differentiating wear on the basis of different points of the surface. Disadvantages of this method: relatively high error of instruments which, if wear value is not high, may be commensurable with wear value; the need in arrangement of coupling for each measurement, which results in deviation of wear process [20].

Weighting method is used for measurement of total wear (total weight loss) on friction surface. The benefits of this method: simplicity, accessibility and relatively high accuracy. Disadvantages of this method: inability to differentiate wear on the basis of different points of the surface; the need in arrangement of coupling for each weighting; inability to apply this method to materials, charged with wear products or foreign particles and also materials that absorb moisture or oil [20].

The method for detection of wear products in oil. This method is based on periodical collection of oil samples. Wear rate is determined on the basis of the number of products in oil samples. The quantity of products is determined by chemical or spectral analysis. The benefits of this method: possibility for measuring wear without arrangement of coupling; high sensitivity. Disadvantages of this method: inability to determine wear of each part separately (this methods allows changing total wear of entire coupling); complexity [20].

Integral detector method determine wear of the part on the basis of measurement of linear dimensions (or position) of such part, determined by detector, built into coupling. Different displacement detectors (inductive, pneumatic, strain-measuring etc.) may be used. The signals, transmitted by these detectors, is recorded by logger, oscillometer etc. Benefits of this method: relatively high accuracy; possibility for measuring wear without decoupling of surfaces and also continuous and uninterruptable measurement of the wear. Disadvantages of this method: complexity of this method, very complex and sometimes even impossible to separate measurement of the wear of coupling parts [20].

Wear maps are one of the most critical methods for representation of data, obtained in the course of testing of some materials for wear. Wear maps that represent wear data in graphical form provide global view of material behavior at different wear rate. They also determine main wear mechanisms at different conditions and ensure prediction of excepted wear rate. Wear maps resemble phase diagrams in terms of complexity of their plotting. In spite of great amount of test data it is also necessary to use calibrated wear models in order to predict wear behavior and rate [17].

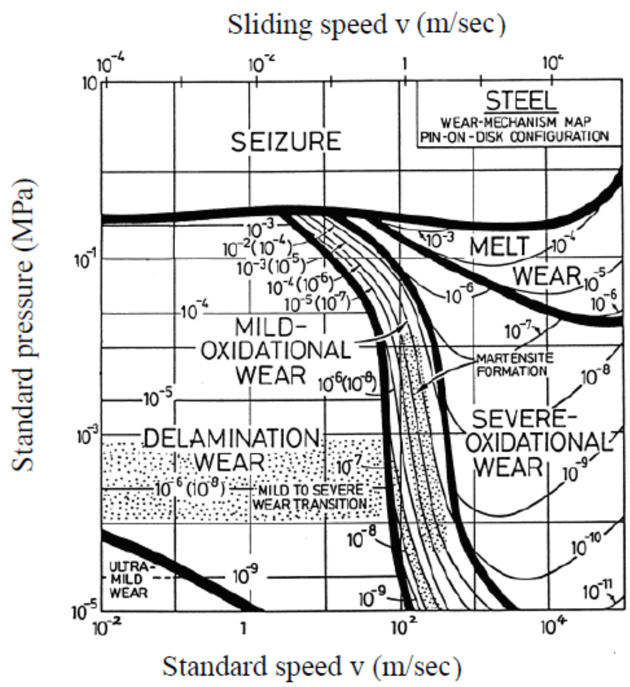
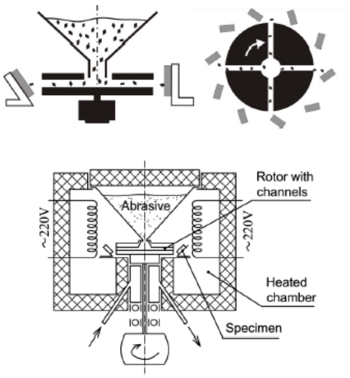
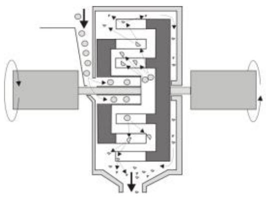
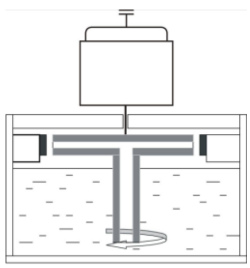
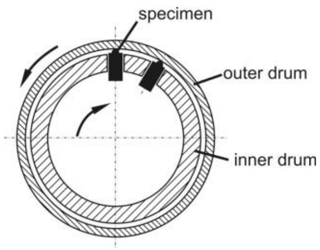


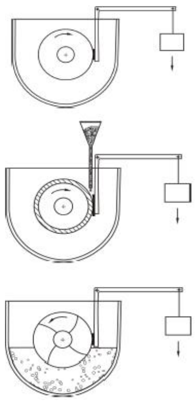
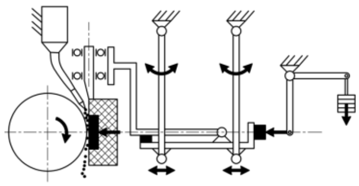
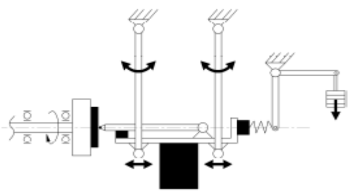
Figure 5. Wear mechanism for steel [17]

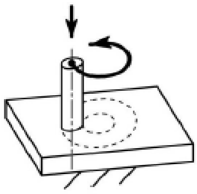
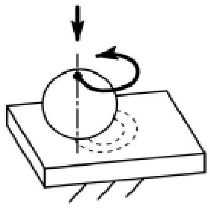
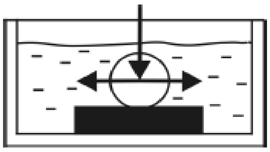
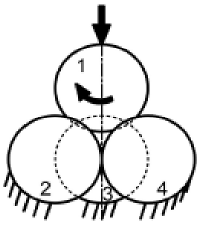
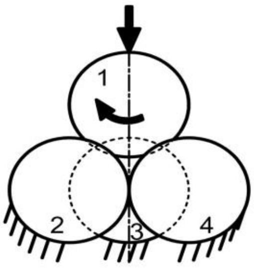
3.6 Wear measurement hardware, available in Tallinn University of Technology

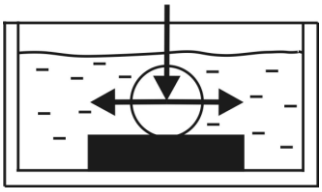
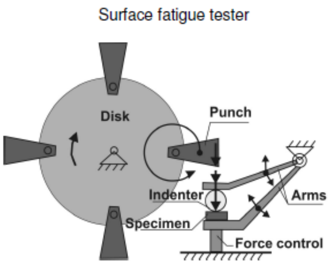
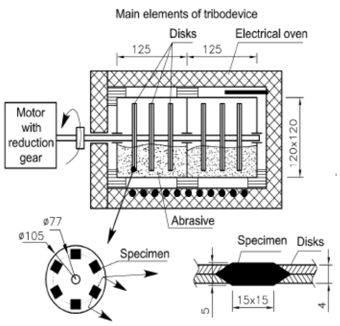
Below is presented the list of wear measurement hardware available in Tallinn University of Technology [18].

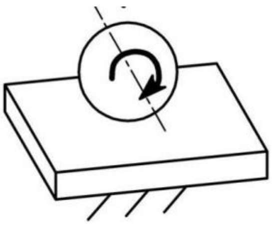
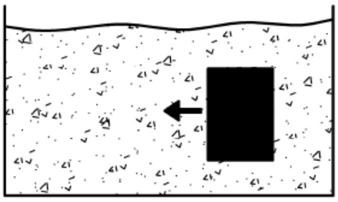
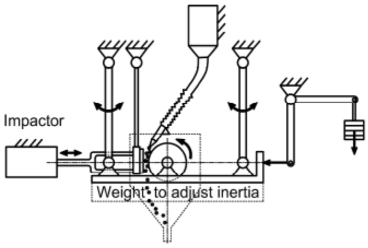
Type of wear	Scheme	Description / Parameters	Applicable standard
Abrasive erosion (AEW) ►At room temperature ► At high temperature 20 - 650 °C (possible to make with **inert gas** as well)	Centrifugal accelerator 	Impact angle 15-90° Impact velocity 0-80 m/s Abrasive size 0.05-1.00 mm 15 / 20 samples at once (room temperature / high temperature tester)	GOST 23.201-78 ASTM G76-07 BS EN 60587:2007
Abrasive impact wear (AIW)	Disintegrator type Impact wear tester 	First collision velocity 40-125m/s, second max 200m/s Abrasive size up to 7 mm 14+14 samples at once	For specific custom conditions
Slurry erosion (SEW)	Centrifugal type slurry erosion tester 	Impact velocity: 3-35 (usually 20 m/s) Abrasive particle concentration: up to 60 wt. %. Slurry is moving along the cylinder formed by samples (impact angle is close to zero). 30-35 samples at once	ASTM G75-07 G73-04

Sliding wear	Centrifugal type drum tribometer  	Specimens with spherical tip (solid and coated) Force depends on velocity of inner drum (0-20 N). Sliding velocity is controlled by outer drum. Up to 12-16 samples at once Velocity up to 30 m/s	ASTM G132-96 G99-05

Type of wear	Scheme	Description / Parameters	Applicable standard
Block-on-Ring ► Sliding wear (without abrasive) ► Abrasion (with abrasive) ►With abrasive slurry	Block-on-Ring tester 	Disks: ø228.6 mm (steel) ø228.6 or 80.0 mm (rubber). Excitation of abrasive slurry is available. Velocity 0.1-15 m/s Force 1-250 N One sample test	ASTM G65-04 B611-85 G105-02 G137-97 G77-05e1
Sliding wear with or without abrasive	Block-on-Ring with COF recording  Ball-on-Flat and Pin-on-Flat Possible to study effect of loading system inertia 	Block (1-10)x(15-25)x(25-50) mm Ball ø 3 mm Temperature 20 – 450 ºC (in Block-on-Ring scheme) Normal force 0 – 200 N Dead-weight loading Speed 30 - 700 rpm One sample test	ASTM G65-04 G105-02 G137-97 G77-05e1 ASTM G132-96 G99-05

Type of wear	Scheme	Description / Parameters	Applicable standard
Sliding and fretting wear by Universal tribometer UMT2 (from CETR now Bruker)	Continuous sliding mode. Spiral and butterfly tracks are also possible.   Fretting mode.  	Ball-on-Flat and Pin-on-Flat geometries Ball ø 3; ø10 mm Normal force 0.1 – 200 N Servo-controlled loading with springed suspension. Sliding: Speed 0.1 - 1000 rpm Temperature 20-1000°C Possible with inert gas Fretting: Stroke 0.1 - 25 mm Frequency 0.1 – 25 Hz Control of humidity is available One sample test Four-Ball method: Balls 0.5' (12.7mm) Torque 0.1-22.6 N m Load max 200 N	ASTM G132-96 G99-05 ASTM D4170-97 G133-05 D5706 D5707 DIN 51834-1 51834-2 ASTM E92-82 D4172
Four-Ball method for oil testing		Balls 0.5' (12.7mm) Torque max 25 N m Rotational frequency 100-3000 rpm Load max 10000 N	ASTM D2266 D2596 D2783 D4172 D5183

Type of wear	Scheme	Description / Parameters	Applicable standard
Fretting wear Wazau SVT500 with air bearings	Fretting wear tribometer 	Ball-on-Flat and Pin-on-Flat geometries Liquid media available Ball / pin: ø6 – 10 mm Stroke +-2.0 mm Frequency 0.1 – 40 Hz Temperature 20 – 150 ºC Normal force 0 – 500 N Dead-weight loading	ASTM D4170-97 G133-05 D5706 D5707 DIN 51834-1 51834-2
Surface fatigue wear (SFW)	Surface fatigue tester 	The energy of the impact depends on the weight of the punch and the velocity (3-500 mJ). Frequency of impacts 12-100 Hz Diameter of the indenter 5-20mm One sample test	ASTM D2794-93 D3170-03
Abrasion-oxidation		Velocity 0-0.1 m/s Temperature 20 – 900 ºC Pressure expressed by abrasive 200-400 Nm-2 Possible testing in two abrasives at once; 18+18 samples at once.	For specific custom conditions

Type of wear	Scheme	Description / Parameters	Applicable standard
Sliding wear with or without abrasive (fine abrasive)		Normal force depends on size of ball Ball 15 – 30 mm Speed 20 - 500 rpm Typical abrasive – diamond paste 1 µm One sample test	KaloMax method
Slurry abrasive wear		Continuous sample movement in slurry pot Unidirectional Max 8 samples at once Monitoring of forces (vertical, horizontal)	For specific custom conditions
Abrasive wear with impacts and adjustable inertia value		Low, medium and high stress abrasion with impacting Disks: Ø80 mm (steel, composite or ceramic) Velocity 0.1-3.0 m/s Force 10-250 N Impact energy 0-19 J Frequency 0-55 Hz Abrasive max 1 mm Inertia max 200 kg One sample test	For specific custom conditions like drill bits, etc

4 GOALS AND TASKS

The goal of this graduation thesis is the tribological study of covered medium voltage overhead lines conductors. It is required to select the conductor (cable) with highest resistance against wear by wood (imitation of tree fallen during storm) to ensure uninterrupted supply of Estonian customers by electricity. The list of necessary tasks has the following form:

- Examine the literature related to covered medium voltage overhead lines conductors (cables)
- Examine the literature related to rubbing and wear
- Explore the Block-on-Ring machine in order to test the cables.
- Choose the most convenient parameters for tests.
- Elaborate marking of tested cables, in order to make the study case more reliable.
- Test the covered medium voltage overhead lines conductors (cables) in different conditions and with different loads.
- Analyse received results
- Make conclusions on the basis of received results

5 DEVELOPMENT OF THE TEST TECHNOLOGY

5.1 Calculation method

It is possible to calculate the ring perimeter using Equation 3.

$$L = \pi \cdot d \,, \tag{3}$$

π - number Pi, which equals 3.14159265359,

d - wheel diameter, m.

Knowing the wheel perimeter, the velocity and time of wheels rotation it is possible to calculate the sliding distance, using Equation 4.

$$s = L \cdot v \cdot t \,, \tag{4}$$

L - perimeter length (found with Equation 3), m

v - rate of rotation (set according to requirements, considering gear box reduction ratio, in units of measure, rpm)

t - time of test (set according to requirements, in units of measure, min)

Steel and wooden wheels have different diameter (steel – 0.172 m, wooden 0.135 m), therefore it is necessary to recalculate rate of rotation to ensure same sliding speed.

As the path length depends on wheel diameter the additional coefficient for the wooden wheel will be expressed with Equation 5.

$$\frac{d_{metal}}{d_{wood}} \,, \tag{5}$$

d_{metal} - steel wheel diameter, m,

d_{wood} - wooden wheel diameter, m.

Additional coefficient for the wooden wheel will be equal

$$k = \frac{172}{135} = 1.274$$

Therefore, if steel wheel will rotate with velocity of 766 rpm, the wooden one should rotate with velocity according to Equation 6.

$$v_{metal} = k \cdot v_{wood} \ , \qquad (6)$$

k - additional coefficient,

v_{wood} - rotation velocity of wooden wheel.

$v_{metal} = 1.274 \cdot 766 = 975.88$ rpm (according to Equation 6)

The wear area of cables samples can be found using Equation 7.

$$S_{wear} = h_{wear} \cdot l_{wear} \, , \qquad (7)$$

h_{wear} - depth of wear mm,

l_{wear} - length of wear mm.

The depth of wear from wear area is calculated by Equation 8.

$$h_{wear} = \frac{S_{wear}}{l_{wear}} \, , \qquad (8)$$

S_{wear} - wear area mm,

l_{wear} - length of wear mm.

The average wear was calculated by Equation 9.

$$A = \frac{S}{N} \, , \qquad (9)$$

S - the number of terms,

N - the sum of the numbers in the set of interest.

5.2 Test metchnology of samples with Block-on-Ring machine

5.2.1 Devices and test samples

In order to provide testing of cables, in this practical work the Block-on-Ring machine was used. As we see from chapter 3.6, this machine lets exercise tests according to the following standards:

- ASTM
- G65-04
- B611-85 (main)
- G105-02
- G137-97
- G77-05e1

You can see the structure of this machine in Drawing 1.

The Block-on-Ring machine was chosen because of the following reasons:

- First of all, 5 cables can be tested simultaneously with this device.
- Secondly, wet tests (with addition of liquid) are possible.
- Thirdly, this device is not expensive to use.
- Fourthly, the machine was available at the time of tests.

Two types of wheels were used for testing of cables.

- The wooden wheels that had 135 mm diameter and 11.5 mm of working surface width.
- The steel wheels that had 172 mm diameter and 14.0 mm of working surface width.

The cables with sheaths from Table 1 were used for testing.
There were 10 samples given for test that differed between each other in such parameters as diameter, material of sheaths, presence of semiconductor layer, number of insulation layers, color.

5.2.2 Description of Block-on-Ring machine

The Block-on-Ring machine is composed of electric motor, protective cup, shaft, wheels, levers, which apply the cables samples to the working surface of wheel, weight, bowl and - frequency controller for the electric motor rotations regulation.

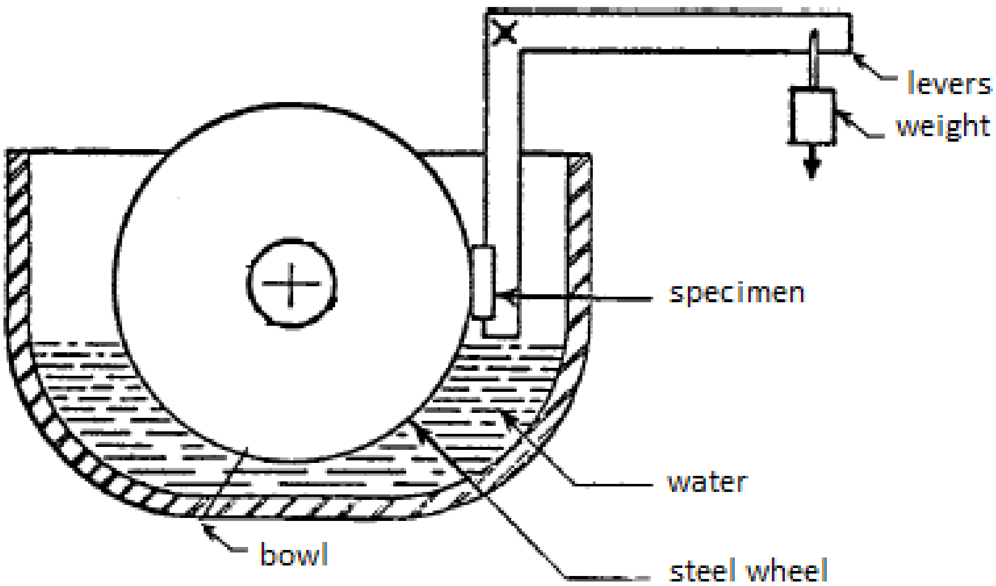


Figure 6. Principal scheme of Block-on-Ring machine [18]

To understand better the structure of Block-on-Ring machine, see Figure 7 or Drawing 1.

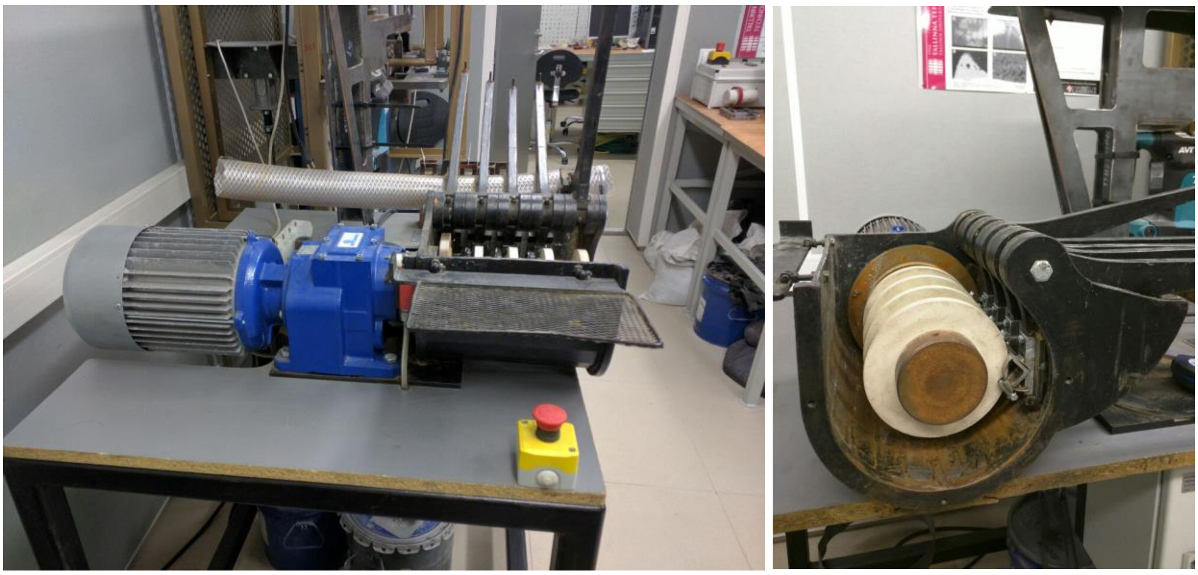


Figure 7. Block-on-Ring with wooden wheels before dry test

5.2.3 Covered medium voltage overhead lines conductors (cable types) for testing sheaths

In order to test wear of cable sheaths upon their friction on the wood 10 cable models were used. In order to simplify testing and further analysis all cables were assigned sequence numbers (ID) from 1 to 10. You can see models and their sequence numbers (ID) in Table 1.

Table 1. Cable specifications and sequence numbers

Cabel ID	Cable manufacturer	Matarial of sheaths	Semiconductor layer	Number of insulation layers	Adhesion between the outer layers
1	////	Polyethylene	+	2	+
2	///	Cross-linked polyethylene	+	2	-
3	/	Polyethylene	+	2	-
4	///	Polyethylene	+	2	-
5	/	Cross-linked polyethylene	+	1	-
6	/	Cross-linked polyethylene	+	1	+
7	/////	Polyethylene / Cross-linked polyethylene	+	2	-
8	//	Polyethylene	+	2	+
9	//	Polyethylene	+	2	+
10	/	Cross-linked polyethylene	-	1	

Since the cable manufacturer data and their wear results are confidential, the cable manufacturers were designated as /, //, ///, ////.

The most important different is the material of the sheath.. The cables provided for testing have polyethylene or cross-linked polyethylene types of sheaths.

Polyethylene (PE) is used most in coaxial and low capacitance cables because of its exemplary electric qualities. Many times it is used in these applications because it is affordable and can be foamed to reduce the dielectric constant to 1.50 (cross-linked polyethylene have 2.25), making it an attractive option for cables requiring high-speed transmission. Polyethylene can also be cross-linked to produce high resistance to cracking, cut-through, soldering, and solvents. Polyethylene can be used in temperatures ranging from

-65 °C to 80 °C. Polyethylene of all densities is stiff, hard, and inflexible. The material is also flammable. Additives can be used to make it flame retardant, but this will sacrifice the dielectric constant and increase power loss [20].

Dielectric constant (*k*) is a number relating the ability of a material to carry alternating current to the ability of vacuum to carry alternating current [19].

Cross-linked polyethylene (XLPE) is a thermosetting compound which has better electrical properties than PVC (polyvinyl chloride) and is therefore used for medium- and high-voltage applications. It has more resistance to deformation at higher temperatures than PVC, which it is gradually replacing. It is also replacing PILC (Paper-Insulated Lead Cable) in some applications. Thermosetting insulation may be used safely with conductor temperatures up to 90 °C thus increasing the useful current rating, especially when ambient temperature is high. A LSF (low smoke and fume) type of thermosetting cable is available [21].

You can see comparison of materials tested in current work in Table 2.

Table 2. Comparison of materials tested in current work [22]

Material	**Advantages**	**Disadvantages**
PE	• Lowest dielectric losses • High initial dielectric strength	• Highly sensitive to water treeing • Material breaks down at high temperatures
XLPE	• Low dielectric losses • Improved material properties at high temperatures • Does not melt but thermal expansion occurs	• Medium sensitivity to water treeing (although some XLPE polymers are water-tree resistant)

5.2.4 Preparation for test

The first stage during preparation for tests is examination of wheels condition. The examination consists in visual check of wheels surface quality (steel and wooden), and of wheels in general. This stage is very important as the quality of test results depends on this.

The main defect in steel wheels is a rust film, which appears after wet tests. The example of such film is well seen on Figure 8.

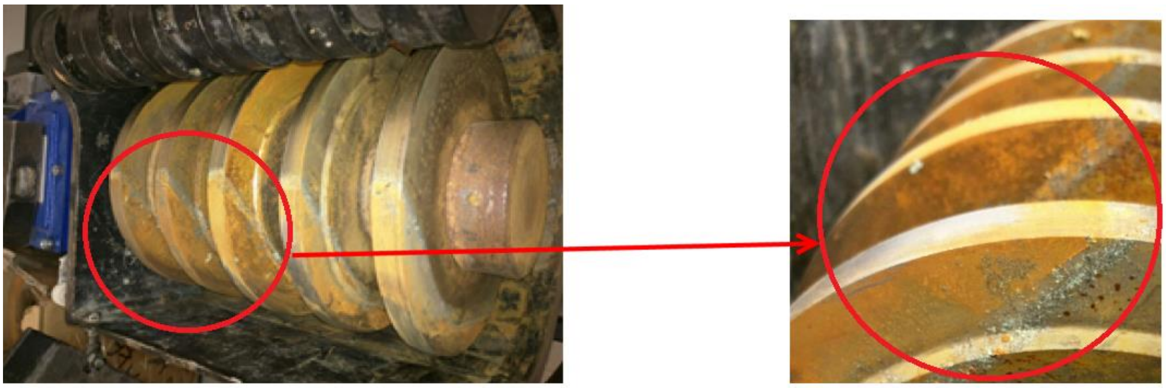


Figure 8. Rust film on steel wheel after wet tests

Also one of the possible defects after tests is appearance of cable cladding coating on surface.

All the mentioned above defects can be removed from steel wheels with a help of grinding paper P180 (Buenhler-Met Silicon Carbide grinding paper. Average particle diameter 82 μm). This type of grinding paper lets work with both dry and wet wheel. The gritness of this grinding paper also possesses necessary qualities.

The main fine defect of wooden wheels is a film on cable cladding, it was removed with a helped of metal file 2821-0109 GOST 1465-80.

Also after the dry test it was necessary to wait for wooden wheels to cool otherwise there was melting of sheath on some cables, which can be well, seen on the Figure 9.

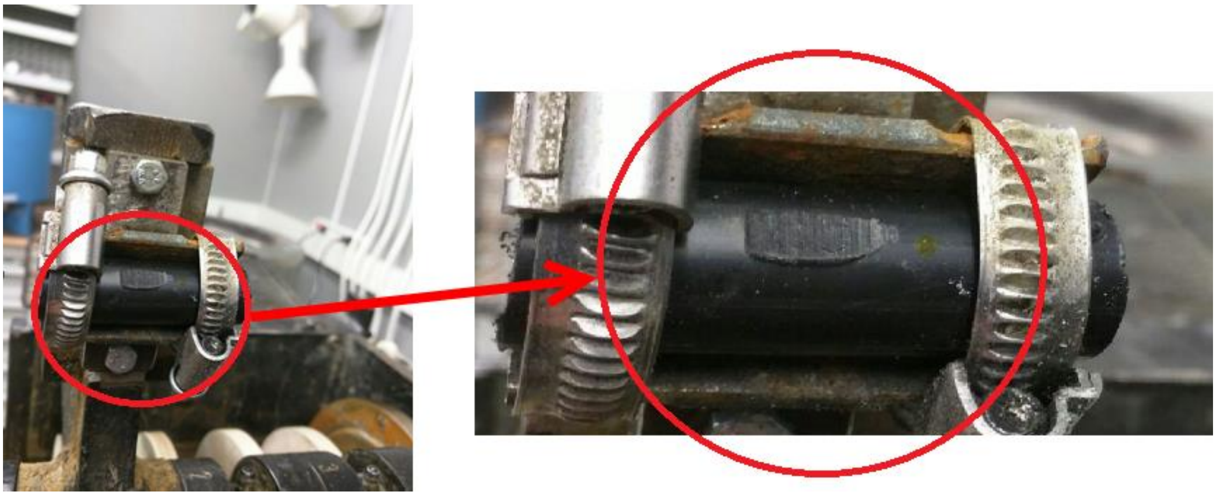


Figure 9. An example of cable sheath melting and deformation after a dry 10 minute test with wood wheel

After all the necessary procedures with wheels are done, the process of samples preparation for tests begins. The length of samples of each cable is 45 mm. This size depends on the Block-On-ring test machine size (holder and width of wheel).

Before the tests the samples are marked so that after the test it could be possible to identify the sample. After this the samples are fixed on the holders of machine. After all 5 samples are being fixed; its contact with wheel is checked by visual examination. In case when cable is not firmly against the wheel, the re-fixation is made.

5.2.5 Tests

On controller from ABB (Figure 10) the rate of motor rotation (taking into account the reduction ratio of gearbox 6.89) and test time are set.

Figure 10. Controller from ABB manufacturer

The rate is set depending on the wheels diameter. The diameter of wooden wheels is 135 mm and the rate of motor rotation is set on velocity of 975 rpm to reach sliding speed of 1 $m \cdot s^{-1}$.

The diameter of steel wheels is 172 mm and the rotations are set on velocity 766 rpm, according to the calculations by Equations 4 and 5 to reach the same sliding speed of 1 $m \cdot s^{-1}$.

In order to exercise the wet test, it is necessary to pour 900 ml of water into bowl, so that approximately 1.5 - 2.0 cm (depending on wheels diameter) of wheel would be immersed in water.

After all the necessary characteristics of test are set, the cable sheaths testing starts. During the test it is important to control that the load on motor would not exceed 30 % (was 11-17 % during test), also to prevent motor from heating, the cooler was installed.

5.2.6 Test results processing

After samples wear testing we define the average wear by Equation 9, shown in chapter 5.1 and note it in the protocol. If necessary the sampling of needed results is made and the analysis of data is carried out.

In order to make the work with results easier, the template was created, in form of table 6 (protocol) where the results are filled in.

Table 3. Protocol in form of a table for test results filling in

Test time (in minutes)	Disc type (wood/metal)	Test type (Dry/wet)	Motor speed (RPM)	Disc diameter (m)	Disc speed (m/s)	Load	Cabel ID	Diametr (mm)	Attemp 1 (mm)	Attemp 2 (mm)	Attemp 3 (mm)	Average (mm)
10	wood	dry	975	0,135	1	no load	10-1	14,5	1,11	0,83	0,36	**0,77**
10	metal	wet	766	0,172	1	no load	10-10	14,4	0,15	0,1	0,07	**0,11**
10	metal	wet	766	0,172	1	load	10-11	14,39	0,08	0,12	0,06	**0,09**
10	wood	dry	975	0,135	1	no load	10-12	14,63	0,05	0,12	0,04	**0,07**
10	wood	dry	975	0,135	1	no load	10-2	14,5	0,39	0,21	0,43	**0,34**

Table 3 contains such parameters as:

- The length of test 10 minutes / 120 minutes / 540 minutes
- Type of wheel wooden / steel
- Type of test wet / dry
- Frequency of wheels rotation 766 / 975 rpm – depending on type of wheel (sliding speed 1 m·s^{-1})
- ID of cable in formate 10-5-1 (where the first number is an ID of cable, second number is number of cable and the third number is number of wear scar)
- Wheel diameter 0.172 m / 0.135 m
- No (additional) load (2.5 kg or 24.5 N) or (with additional) load (10.0 kg or 98 N)
- Cable diameter in mm
- Test result (wear depth) in mm

6 RESULTS OF TESTING

6.1 Covered medium voltage overhead lines conductors (cables) for testing

Cables wear was measured in place of wear testing. Depths of damage influence the stability of cable and the probability of breakdown.

6.1.1 Overview of cable 1

Figure 11. A sectional view and a top view of cable 1

Cable 1 has black color. The cable outer diameter varies between 15.75 - 16.07 mm. There are 7 conductors in the cable. The sheath material is polyethylene.

The test results are given in Figure 12.

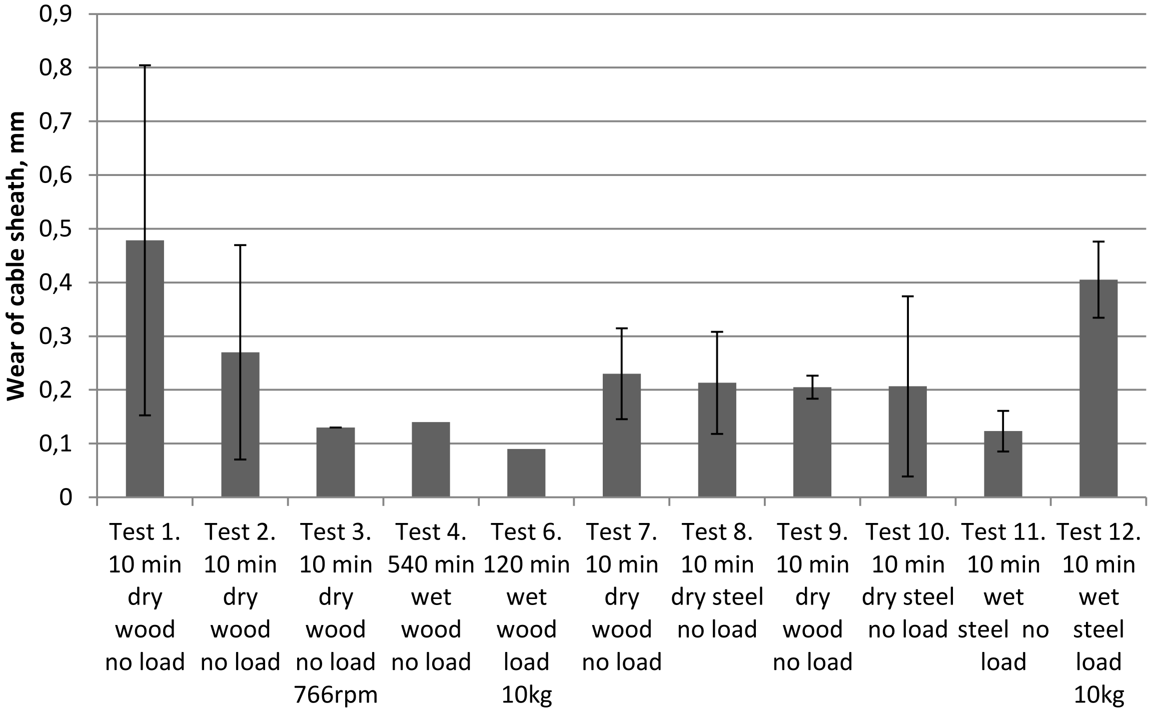


Figure 12. Test results of cable 1, based on Table 6, (no load means load of 2.5 kg)

As we see from Figure 12, the strongest wear happened during first dry test of 10 minutes long with wooden wheel. Such a big wear was conditioned by the fact that it was first test with new wooden wheel, which had a maximal abrasive property (due to the presence of dry glue), already after first test we see that the wheel abrasive property reduced, as a result a wear reduced too during second test.

In the third test the frequency of wheel rotations was reduced, as a result, the wear reduced too. It was conditioned by the fact that the wheel performed fewer rotations for the same period of time that is why the wear was lower.

The fourth test duration was 540 minutes without additional load and if we compare the result with test number 5 which was 120 minutes long but with additional load, at the test number 4 the wear was higher in 0.01 mm or 8 % than at the test number 5.

Tests 7, 8, 9, 10, 11 were done with the same parameters, more specifically without additional load with dry steel wheel. The results of tests number 8, 9, 10 are approximately the same; the wear at test 7 is a little bit higher than average. It happened because it was the first test with steel wheel and abrasive properties of wheel were maximal. The test number 11 showed the lowest wear because with time the abrasive properties of wheel get lower if carry out the mechanical working of the wheel surface. In this case it was not carried out.

Test number 12 showed maximum wear among the tests with steel wheel because this test was carried out under additional load.

6.1.2 Overview of cable 2

Figure 13. A sectional view and a top view of cable 2

Cable 2 has light-green color. The outer diameter of cable varies between 15.6 - 15.77 mm. There are 7 conductors in this cable. The sheath material is cross-linked polyethylene.

The test results are given in Figure 14.

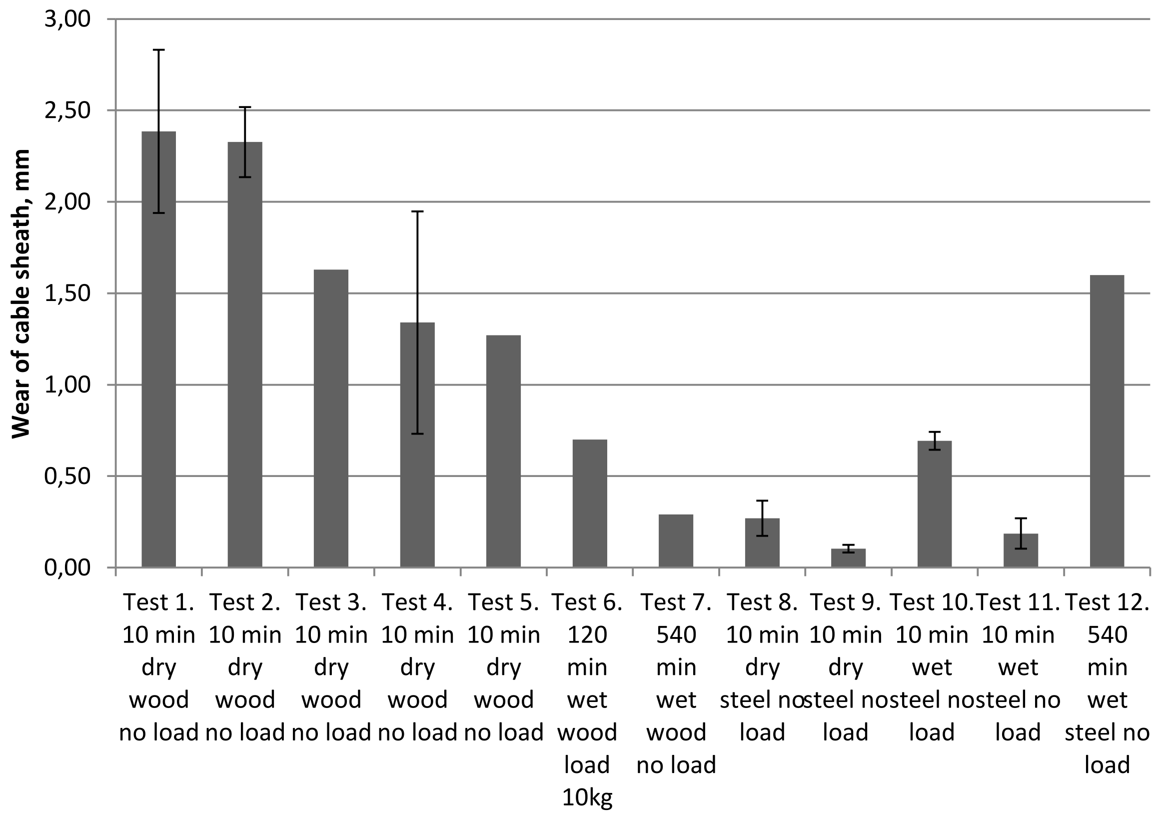


Figure 14. Test results of cable 2, based on Table 7, (no load means load of 2.5 kg)

As we see from Figure 14, the highest wear happened during first dry test of 10 minutes long with wooden wheel. Such a strong wear was influenced by the fact that it was the first test with new wooden wheel, abrasive property of which was maximal, right after first test we see that abrasive property of wheel reduced and as a result the wear reduced at tests number 2, 3, 4, 5.

The wear during wet tests number 6 and 7, with longer time with additional load and without were lower than during dry test. It happened because water in this case served as lubricant, as a result the wear was lower.

Tests number 8 and 9 showed dependency of wear from tests quantity with wheels, as a result, the wear at test number 8 was higher than at test number 9.

During tests 10 and 11 the same tendency was noticed when the wear is higher during first tests than during the following. Test number 12 showed that at the additional load and time increased test, the wear was higher.

In general, cable number 2 showed itself as the most affected by wear (had lowest wear resistance).

6.1.3 Overview of cable 3

Figure 15. A sectional view and a top view of cable 3

The cable 3 has black color. Cable outer diameter varies between 18.5 - 18.65 mm. There are 7 cores in this cable. The sheath material is polyethylene.

The test results are given in Figure 16.

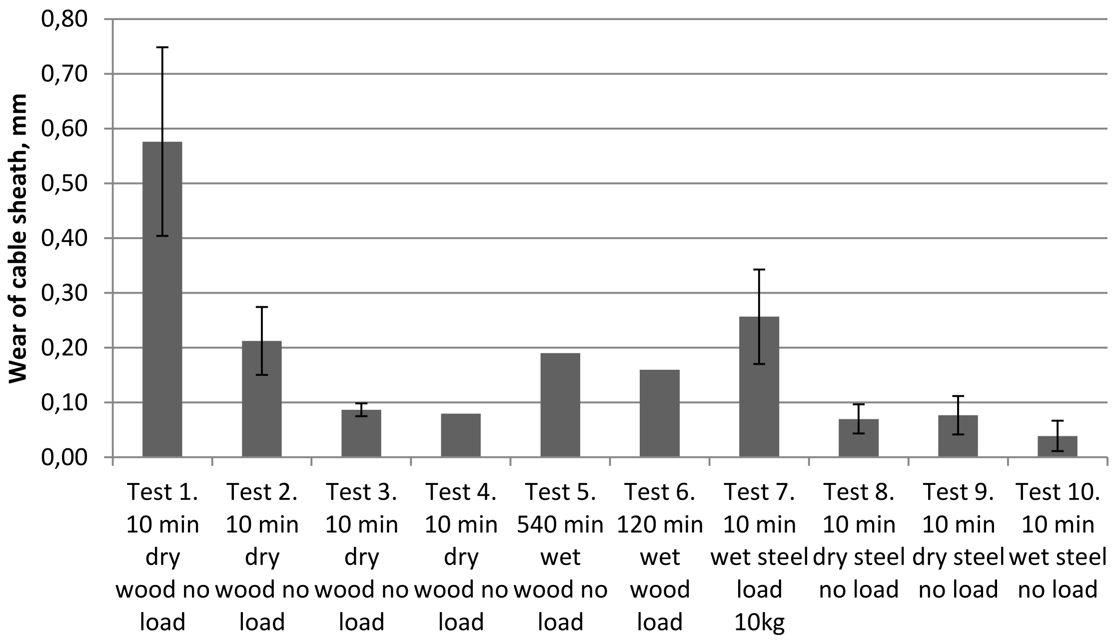


Figure 16. Test results of cable 3, based on Table 8, (no load means load of 2.5 kg)

As we see from Figure 16, the highest wear happened during first dry test of 10 minutes long with wooden wheel. Such a strong wear was conditioned by the fact that it was the first test with new wooden wheel, abrasive property of which was maximal, right after first test we see that abrasive property of wheel reduced and as a result the wear reduced at tests 2, 3, 4.

The wear at wet tests number 5 and 6. The fifth test duration was 540 minutes long and the average wear was 0.19 mm, duration of test number six was 120 minutes long and the average wear was 0.16 mm. The average wear was 0.26 mm at test number 7 even though it lasted less than test number 6 but it was with load of 10 kg.

The wet tests 8, 9, 10 with cable ID 3 showed good results. The wear at test number 9 was a little bit higher than at test 8 it was conditioned by the fact that after 8th test the rust film appeared on steel wheel, which worked as an additional abrasive and the wear grew. After 9th test the steel wheel was smoothed with sandpaper and the wear in next 10th test was lower.

6.1.4 Overview of cable 4


Figure 17. A sectional view and a top view of cable 4

Cable 4 is light-green colored. The outer diameter of cable varies between 15.23 - 15.70 mm. There are 7 conductors in this cable. The sheath material is polyethylene.

The test results are given in Figure 18.

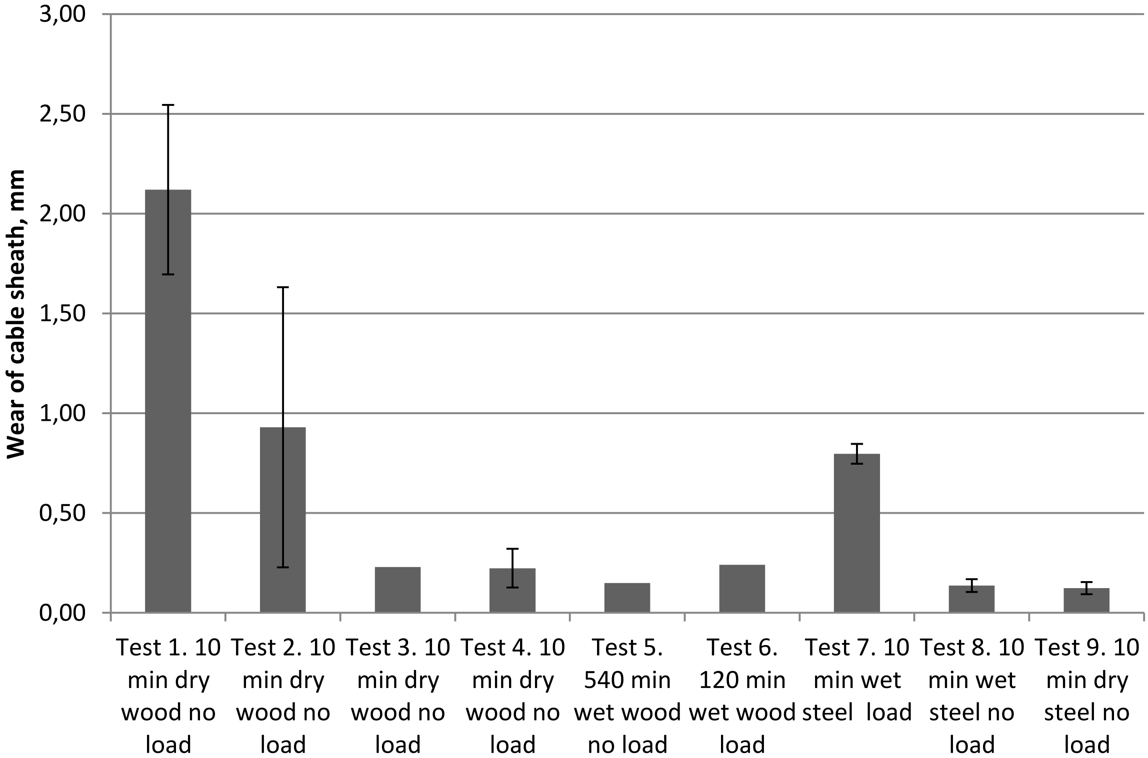


Figure 18. Test results of cable 4, based on Table 9, (no load means load of 2.5 kg)

As we see from Figure 18, the highest wear happened during first dry test of 10 minutes long with wooden wheel. Such a strong wear was conditioned by the fact that it was the first test with new wooden wheel, abrasive property of which was maximal, right after first test we see that abrasive property of wheel reduced and as a result the wear reduced at tests 2, 3, 4.

Cable number 4, during the wet tests, had following wear by steel wheel. Average wear during 120 minutes test with additional load was higher by 0.09 mm, than average wear during 540-minutes test without load. This effect could be connected with the fact that during some time the wheel covers with polymeric coating as a result, its abrasive properties reduce a bit.

After the wet test with steel wheel and with load cable number 4 showed average wear of 0.8 mm. During tests 8 and 9 the average cable wear was similar even though the conditions were different. In first case the test was carried out with water and in second - without.

6.1.5 Overview of cable 5

Figure 19. A sectional view and a top view of cable 5

The cable 5 has black color. Cable outer diameter varies between 16.70 - 16.92 mm. There are 7 conductors in this cable. The sheath material is cross-linked polyethylene.

The test results are given in Figure 20.

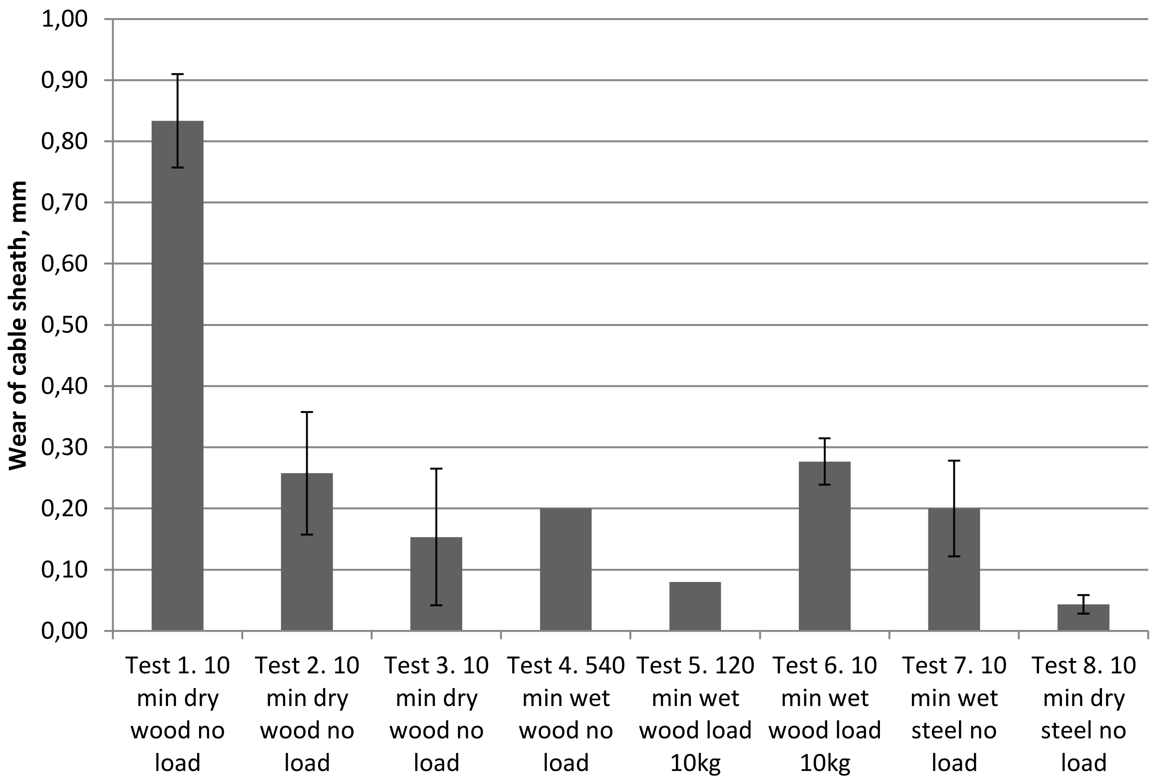


Figure 20. Test results of cable 5, based on Table 10, (no load means load of 2.5 kg)

As we see from Figure 20, the highest wear happened during first dry test of 10 minutes long with wooden wheel. Such a strong wear was conditioned by the fact that it was the first test with new wooden wheel, abrasive property of which was maximal, right after first test we see that abrasive property of wheel reduced and as a result the wear reduced at tests number 2 and 3.

At tests number 4 and 5 the cable number 5 showed the same results as cable 3. At test that lasted 540 minutes, the average wear was higher than during test of 120 minutes with load.

After tests 6, 7, 8 the cable showed logical results. At wet test with load the average wear was higher in 0.08 mm, comparing to next test without load. Final test number 8 showed minimal average wear in 0.04 mm, it was connected to the fact that abrasive properties of wet steel wheel reduced.

6.1.6 Overview of cable 6

Figure 21. A sectional view and a top view of cable 6

The cable 6 has black color. Cable outer diameter varies between 14.84 - 15.00 mm. There are 7 conductors in this cable. The sheath material is cross-linked polyethylene.

The test results are given in Figure 22.

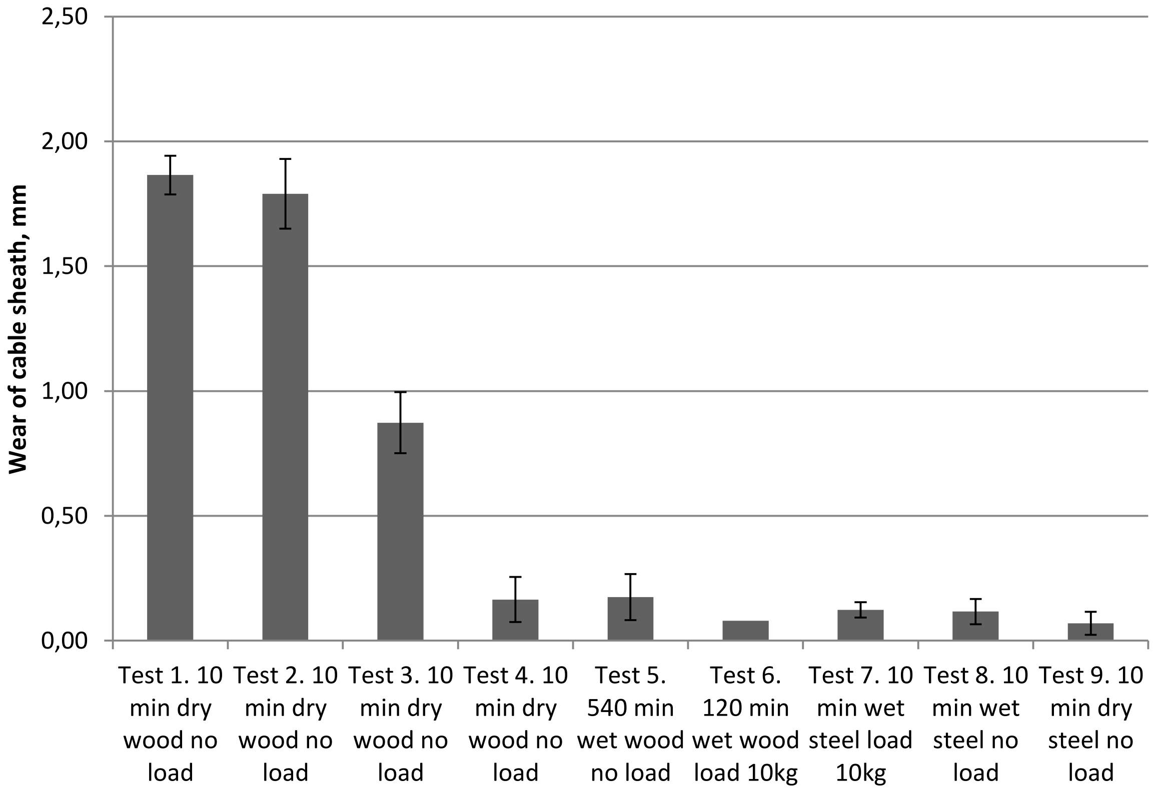


Figure 22. Test results of cable 6, based on Table 11, (no load means load of 2.5 kg)

As we see from Figure 22, the highest wear happened during first dry test of 10 minutes long with wooden wheel. Such a strong wear was conditioned by the fact that it was the first test with new wooden wheel, abrasive property of which was maximal, right after first test we see that abrasive property of wheel reduced and as a result the wear reduced at tests 2, 3, 4.

After tests number 5 and 6 the cable number 5 showed the same results as cables 3 and 5. At test of 540 minutes the average wear was more 0.1 mm, comparing to test of 120 minutes with load.

The average wear of cable 6 during wet test with additional load and without additional load was the same and amounted 0.12 mm, and during next 9th test the average wear was 0.07 mm.

6.1.7 Overview of cable 7

Figure 23. A sectional view and a top view of cable 7

Cable 7 has light green color. The outer diameter of cable varies between 13.87 - 14.00 mm. There are 7 conductors in this cable. The sheath material is polyethylene /cross-linked polyethylene.

The test results are given in Figure 24.

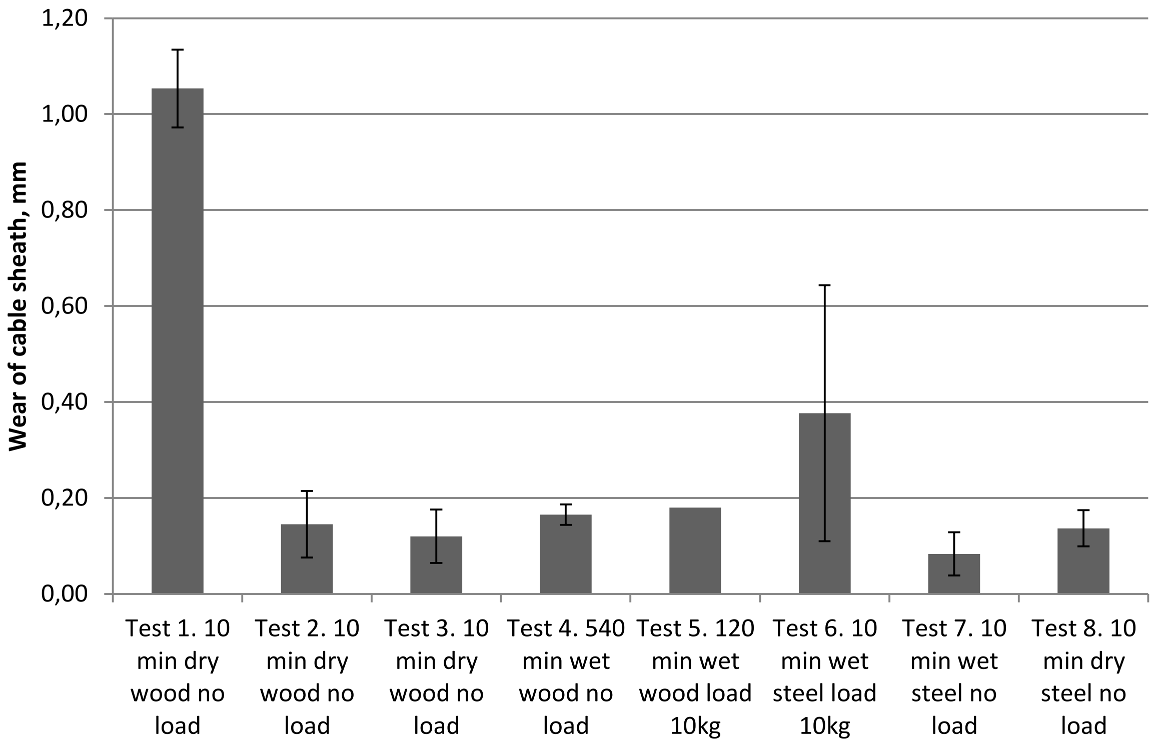


Figure 24. Test results of cable 7, based on Table 12, (no load means load of 2.5 kg)

As we see from Figure 24, the highest wear happened during first dry test of 10 minutes long with wooden wheel. Such a strong wear was caused by the fact that it was the first test with new wooden wheel, abrasive property of which was maximal, right after first test we see that abrasive property of wheel reduced and as a result the wear reduced at tests 2, 3.

After tests number 4 and 5 the cable number 5 showed the same results as cables 4 and 2. At test with duration 540 minutes the average wear was less in 0.1 mm, comparing to test of 120 minutes with load.

The average wear of cable 6 during wet 10 minutes test with additional load and without additional load was the different. For instance, with load the wear was 0.38 mm and without – 0.08 mm.

At dry test without load with steel wheel the average wear was 0.14 mm

6.1.8 Overview of cable 8

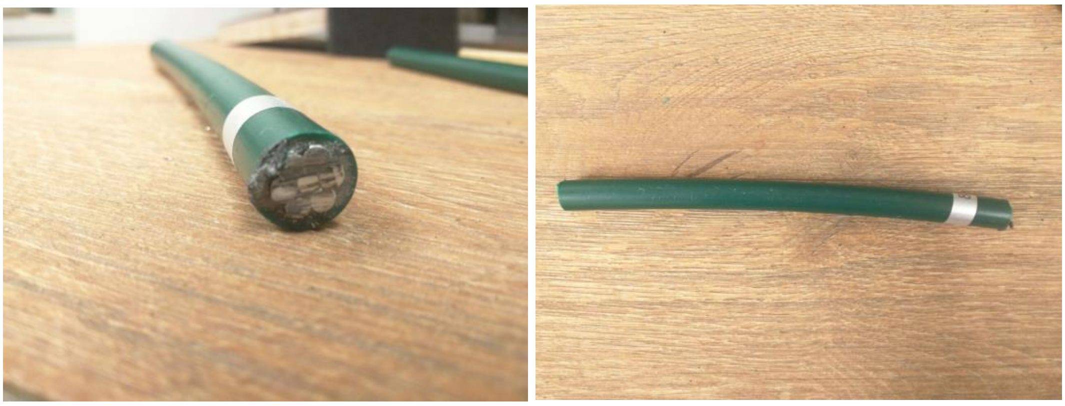


Figure 25. A sectional view and a top view of cable 8

Cable 8 has dark green color. The outer diameter of cable varies between 15.77 - 16.00 mm. There are 7 conductors in this cable. The sheath material is polyethylene.

The test results are given in Figure 26.

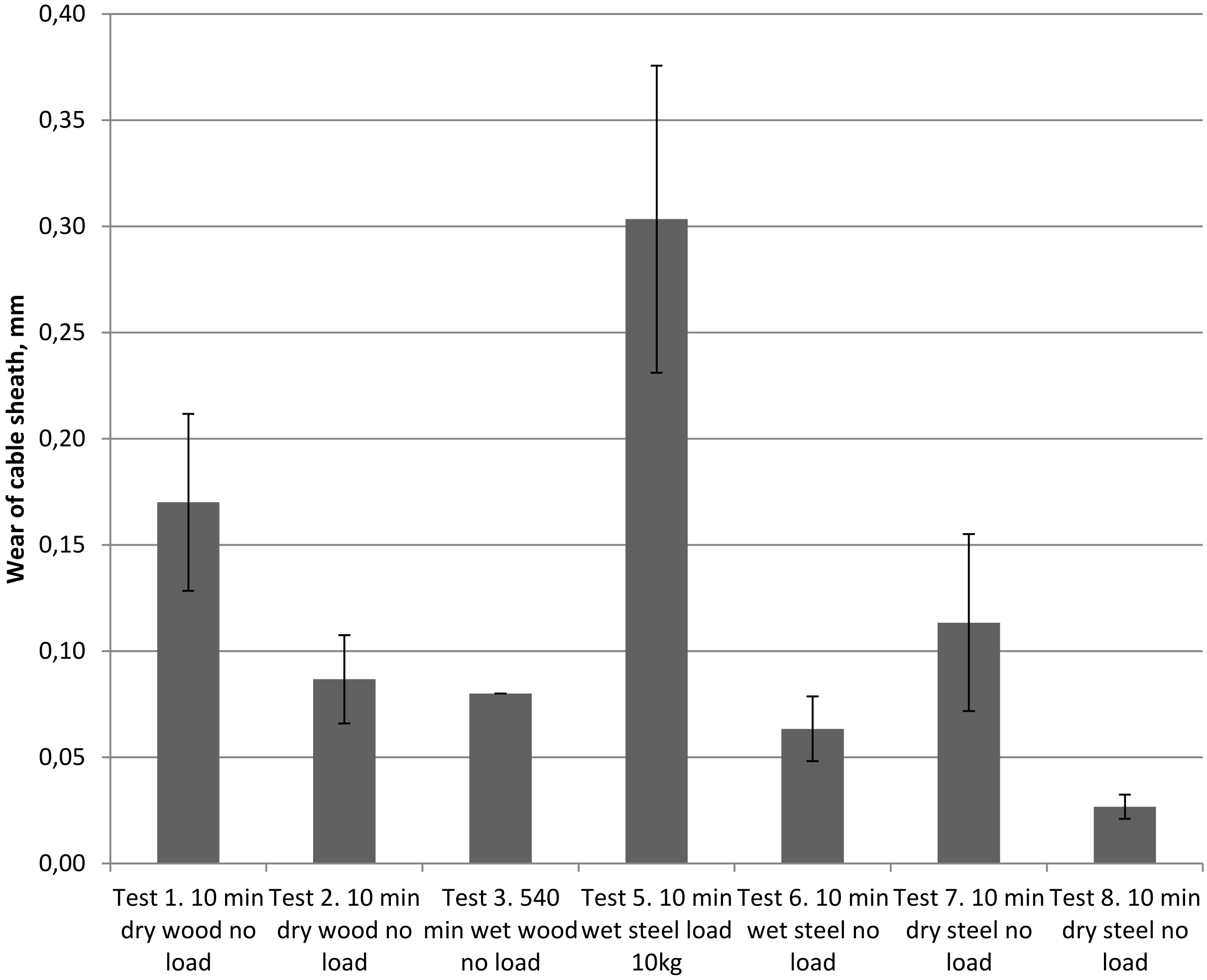


Figure 26. Test results of cable 8, based on Table 13, (no load means load of 2.5 kg)

As we see from Figure 26, the highest wear happened during first dry test of 10 minutes long with wooden wheel. Such a strong wear was conditioned by the fact that it was the first test with new wooden wheel, abrasive property of which was maximal, right after first test we see that abrasive property of wheel reduced and as a result the wear reduced at test 2.

During tests number 3 and 4, the average wear of cable was the same and amounted 0.08 mm, even though it was tested having different parameters. The tests were performed with different duration and load.

The highest average wear cable 8 showed during wet steel wheel and 10 minutes test with load. The wear amounted 0.3 mm. And during wet 10 minutes test but without load, the average wear was 0.06 mm.

During tests 7 and 8 we can notice the loss of abrasive property on steel wheel. The average wear of cable cladding after test 7 amounted 0.11 mm and after test number 8 it was 0.03 mm.

6.1.9 Overview of cable 9

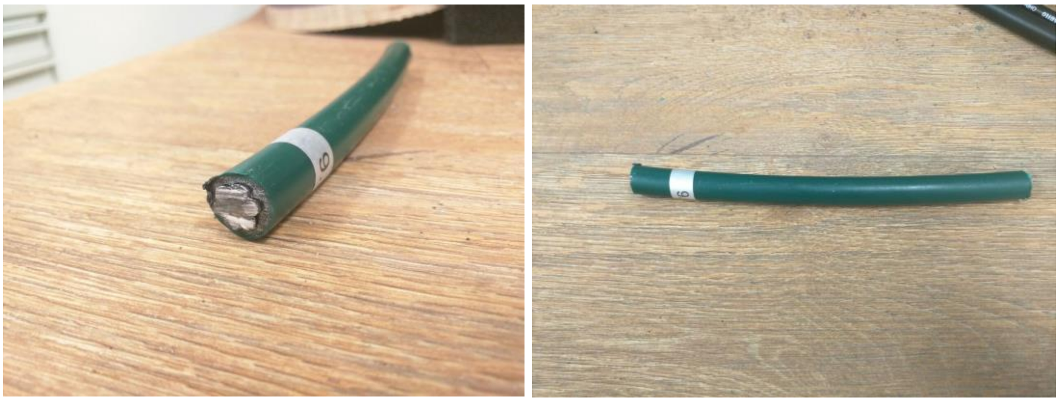


Figure 27. A sectional view and a top view of cable 9

Cable 9 has dark green color. The outer diameter of cable varies between 15.17 - 15.44 mm. There are 7 conductors in this cable. The sheath material is polyethylene.

The test results are given in Figure 28.

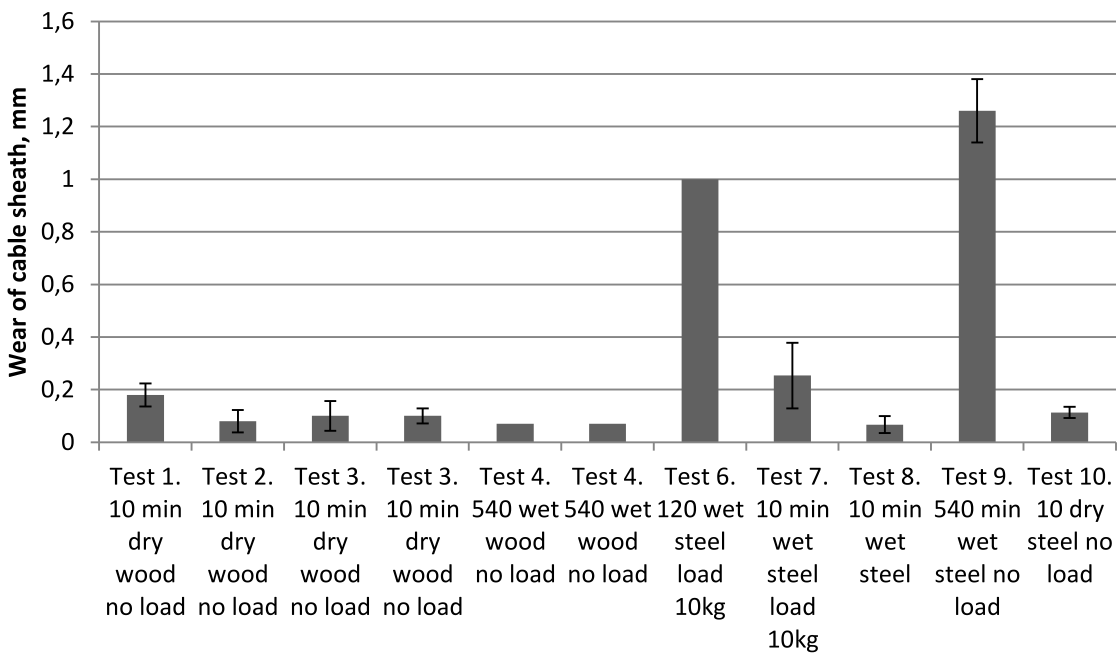


Figure 28. Test results of cable 9, based on Table 14, (no load means load of 2.5 kg)

As we see from Figure 28, the highest wear happened during first dry test of 10 minutes long with wooden wheel. Such a strong wear was conditioned by the fact that it was the first test with new wooden wheel, abrasive property of which was maximal, right after first test we see that abrasive property of wheel reduced and as a result the wear reduced at test 2 and 3. During test number 3 the average wear is a bit higher than during test number 2. It was provoked by the fact that after test 2 the mechanical working of wooden wheel was carried out.

During test number 4 and 5, the average wear of cable was the same and amounted 0.07 mm, even though it was tested with different parameters. The parameters differed between themselves in both – time and load. The same result was shown by cable number 8.

During 120 minutes wet test under load with steel wheel the average wear amounted 1mm. After this test there tests 7 and 8 carried out. Test number 7 was carried out also with load and wet steel wheel but the durability was 10 minutes. The average wear was 4 timed less, 0.25 mm. Test 8 showed result 0.07 mm, it was carried out without load.

The highest average cable wear the cable number 9 showed during wet steel wheel and 540 minutes test without load. The wear amounted 1.26 mm.

Tests 10 and 11 showed the result 0.11 mm and 0.10 mm respectively. These tests were carried out with steel dry wheel and lasted 10 minutes.

6.1.10 Overview of cable 10

Figure 29. A sectional view and a top view of cable 10

The cable is black-colored. Cable outer diameter varies between 14.35 - 14.70 mm. There are 7 conductors in this cable.

The test results are given in Figure 30.

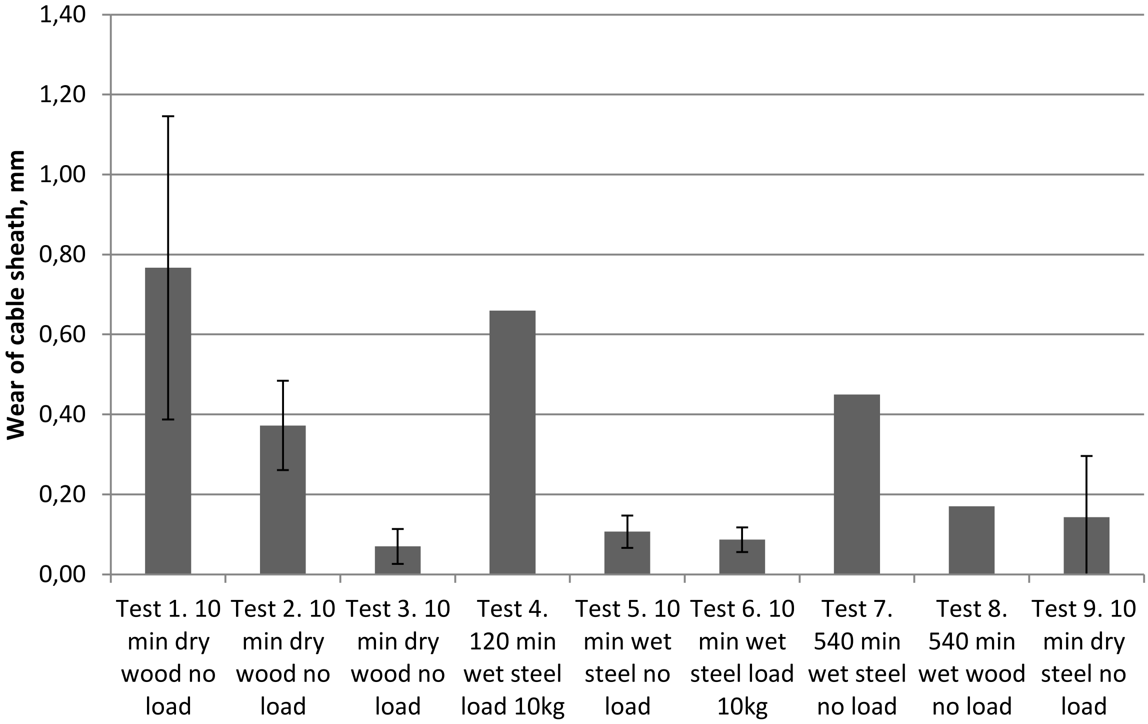


Figure 30. Test results of cable 10, based on Table 15, (no load means load of 2.5 kg)

As we see from Figure 30, the highest wear happened during first dry test of 10 minutes long with wooden wheel. Such a strong wear was conditioned by the fact that it was the first test with new wooden wheel, abrasive property of which was maximal, right after first test we see that abrasive property of wheel reduced and as a result the wear reduced at test 2 and 3.

Average wear at 120 minutes test with wet steel wheel and the load was 0.66 mm. And at 540 minutes test with wet steel wheel without load the average wear was 0.45 mm.

Wooden wheel with cable number 10 showed a little bit different result, the average wear at 540 minutes wet test was 0.17 mm, slightly higher than at the 10 minutes wet test with steel wheel without a load, where the average wear was 0.13 mm.

6.2 Influence of tests number cutting ability of dry wooden wheels

During the cables test on dry wooden wheels, the conclusion can be made, according to Figure 31, that with each test the abrasive properties of the wooden wheels reduce.

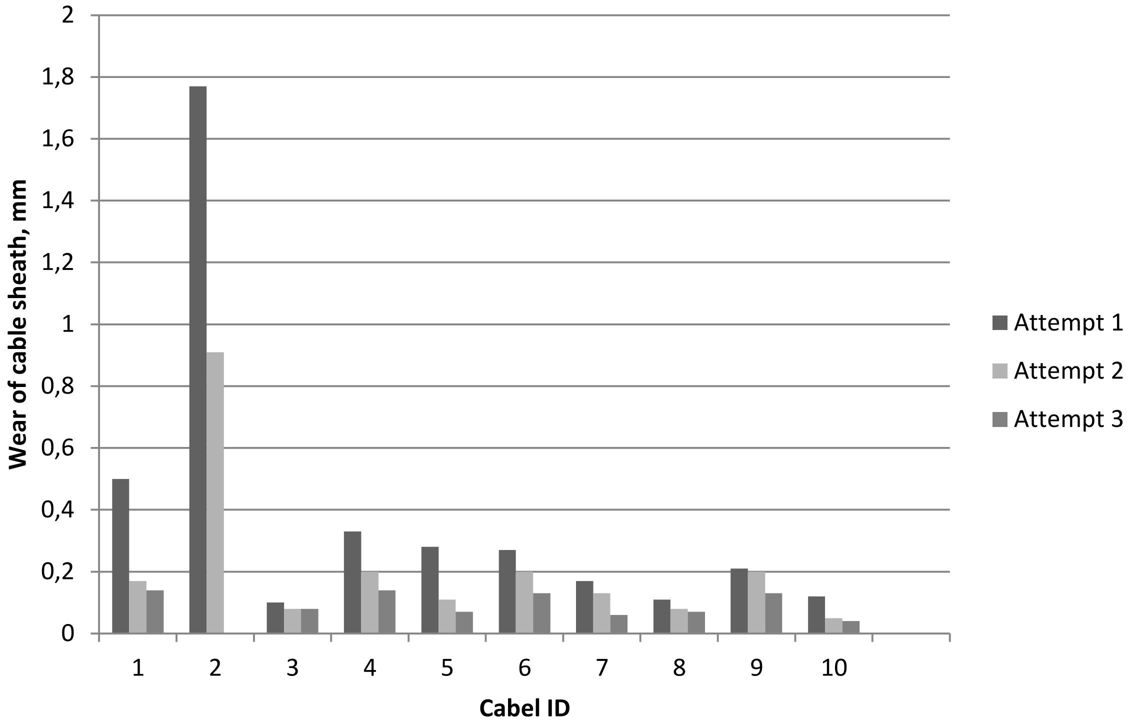


Figure 31. Comparative analysis of the abrasive properties of the wooden wheel after several successive tests (without cleaning of wheel by metal file)

There is an explanation to this phenomenon and it is that the part of cladding is rubbed into wood, thus, the abrasive properties of wheel decrease. For this reason, it was decided after each test to remove a coating of cables cladding from wheels with metal file (2821-0109 GOST 1465-80).

After testing the samples for wear because of the wooden wheels, can be seen that the sample number 2 showed itself from the worst side (the wear was highest), its wear turned out to be many times higher than the average value of wear in other samples.

6.3 Effect of time and load during wet wood wheels tests

Result of testing of cables with wet wooden wheels with an additional load and without. Clear effect was not observed. With load cables were tested 120 minutes with an additional load (total 10 kg) and 540 minutes without an additional load (total 2.5 kg).

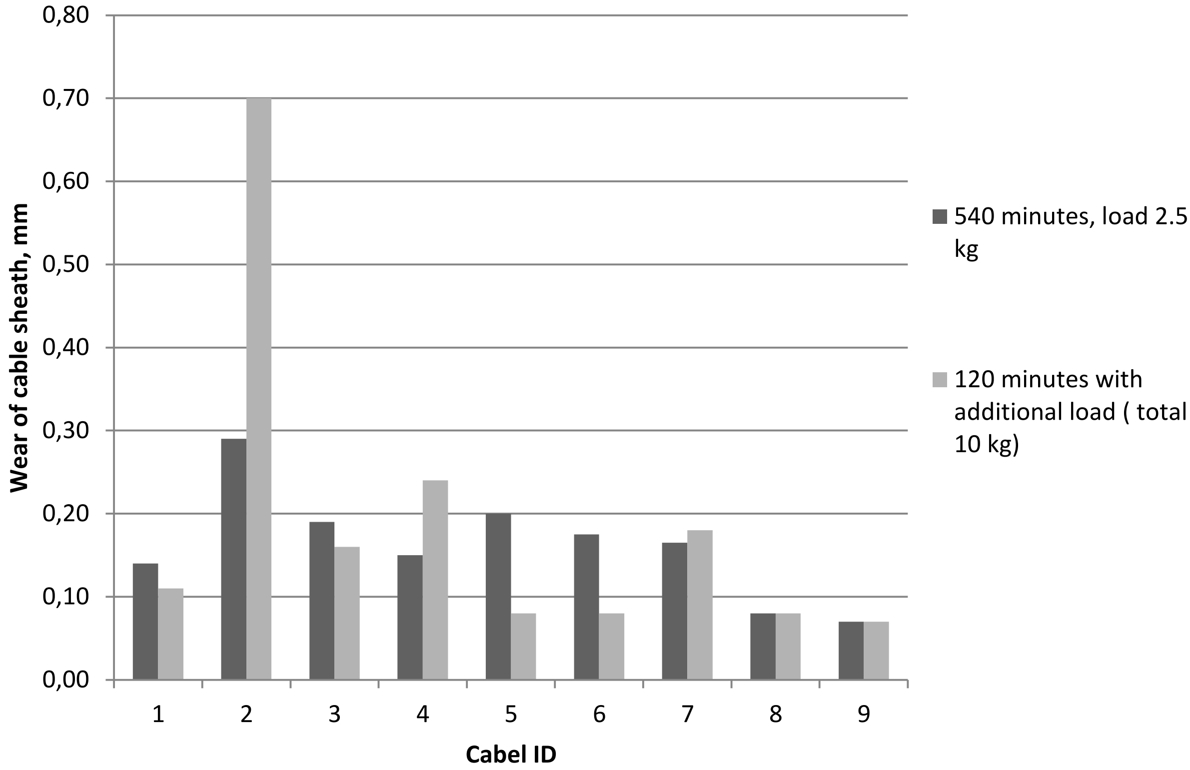


Figure 32. Effect of time and additional load with wet wood wheels tests

As shown on Figure 32. Cables with ID 1, 2, 4 behaved the same way, the wear at 120 minute test with load, was bigger.

Cables with ID 3, 5, 6 behaved differently. The wear during 540 minute test without additional load was larger than wear with the additional load.

Cables with ID 7, 8, 9 showed dependence in which the wear is not depended on the type of test.

6.4 Influence of wet and dry conditions on materials wear.

There were 10 minutes tests carried out to research the influence of presence of water on wear with the steel wheels. Each sample was tested 3 times with each type of test. After each test the samples were re-fixed the way that each new test was realized with new wheel. For this reason the matrix of samples location was drawn up. It is possible to see the matrix in

Table 4.

Table 4. Samples location matrix during tests

Number of lever for samples fixation	Test 1	Test 2	Test 3
1	1	5	4
2	2	1	5
3	3	2	1
4	4	3	2
5	5	4	3

The wear results are presented in Figure 33.

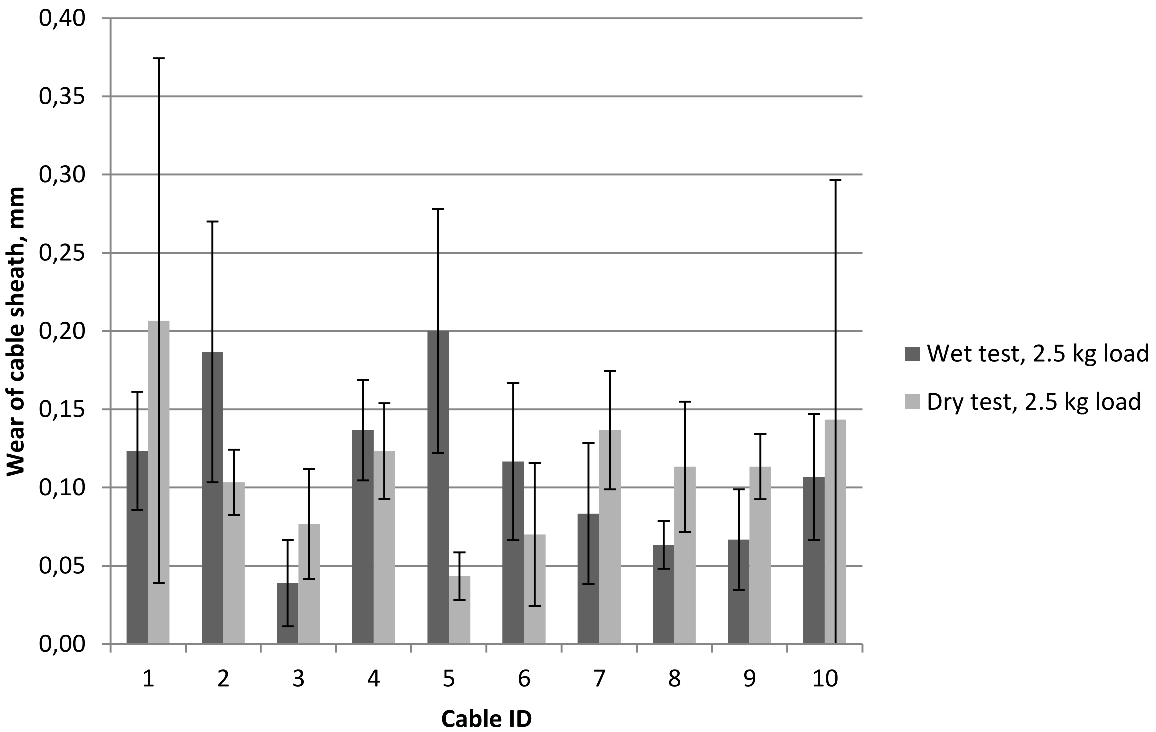


Figure 33. Wear results during dry and wet test with steel wheels

As we see in Figure 33, it is impossible to find a direct correlation between type of test and wear. For example, the wear of cables 2,4,5,6 during wet test was more that during dry and vice verse, cables with ID 1, 3, 7, 8, 9 - less.

6.5 Influence of time on wear during wet test with steel wheels and additional load

There were two tests with two types of cables carried out in order to investigate the influence of time during wet test with load of 10 kg with steel wheels. The cables number 9 and 10 were tested.

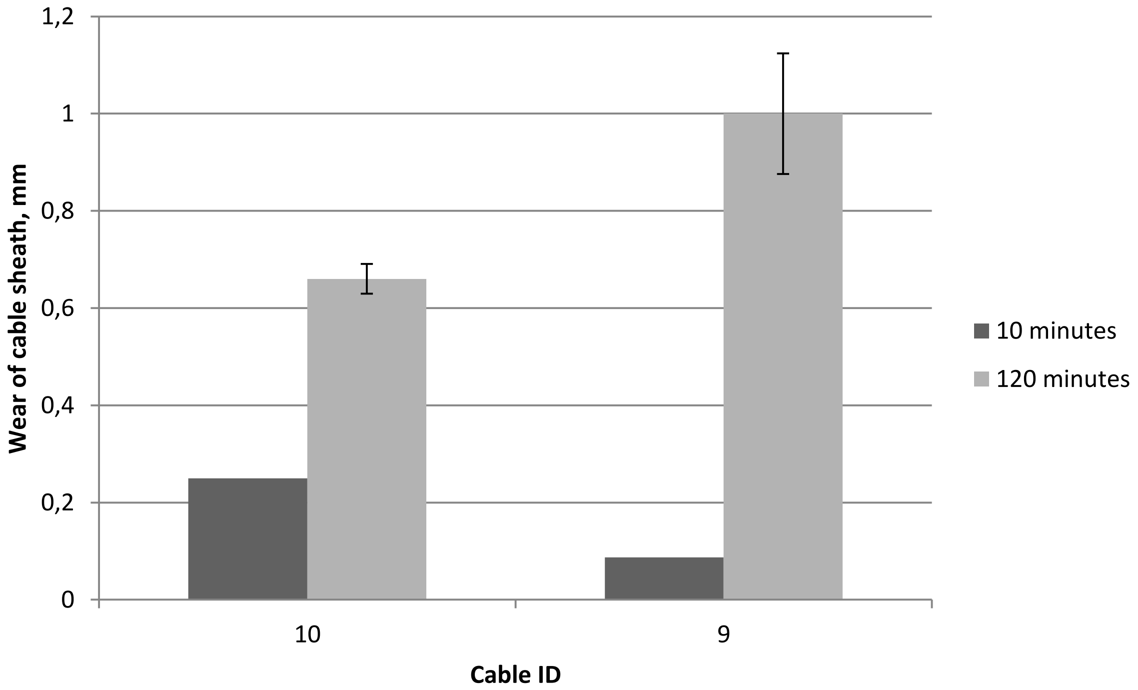


Figure 34. Wear dependency on time at wet test, load 10 kg

As we see in Figure 34 the wear depends on time during wet test.

6.6 Influence of additional load on wear with wet steel wheels

A series of tests was carried out to analyze the influence of load on wear during wet test with steel wheels.

As shown in Figure 35 the wear directly depends on force with which the cable was pressed against the working surface of steel wheel. Also we see that the difference between wear with load and without load is minimal in cables 6 and 10. Most likely, this is due to the fact that they have a harder cladding than cables 2 and 4.

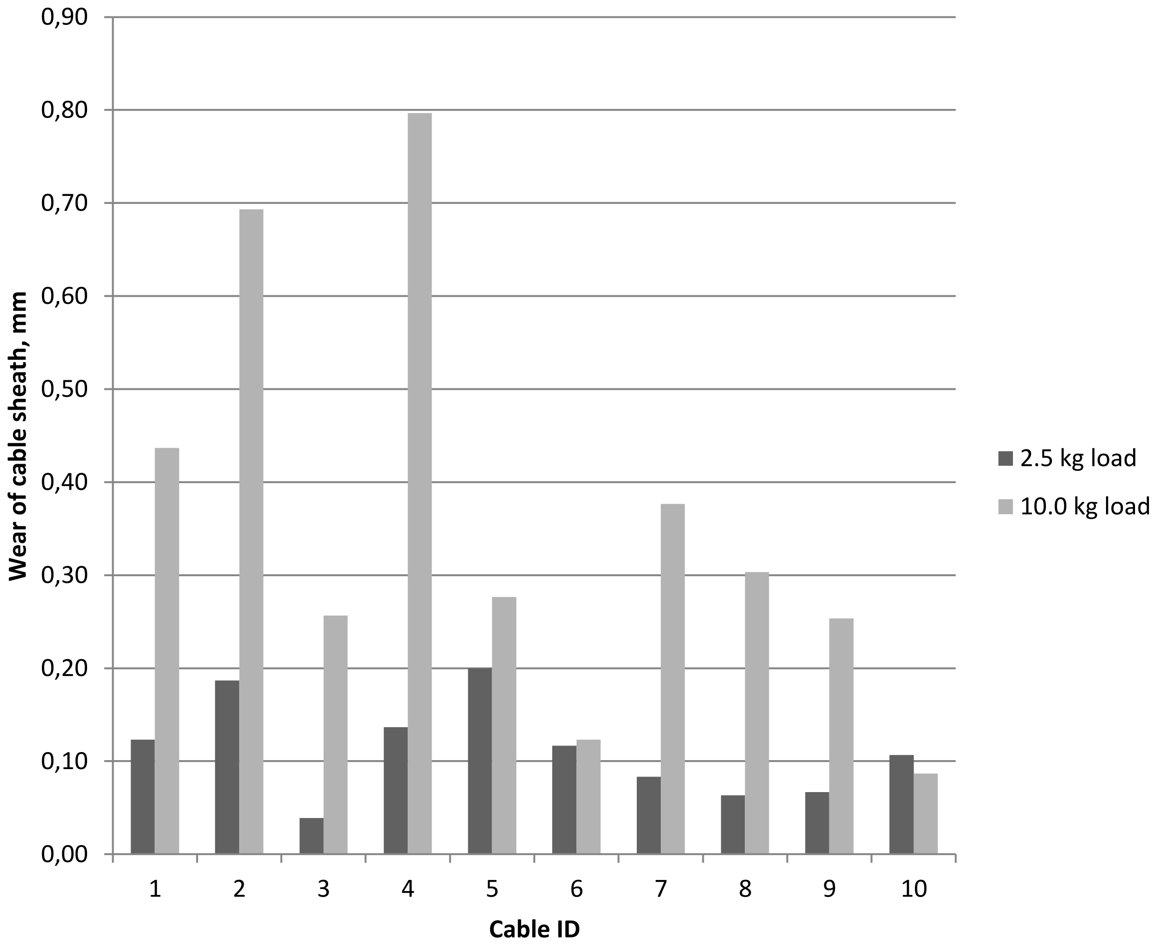


Figure 35. Influence of load on wear during wet test with use of steel wheels, duration 10 minutes

Figure 36. Sample 2 wear (upper) and 10 (lower) after rubbing against wet steel wheel, test duration 10 minutes, load 2.5 kg

As we see on Figure 35 and Figure 36. The sheath of sample 2 was worn more than sample number 10. This difference is observed even by naked eyes.

4.4 Cables examination after the test

After testing, each sample was checked both visually and with the aid of additional tools and using a surface profiler. All samples were researched for wear with a help of a digital calipers. A series of samples was also additionally examined with a help of surface profiler MAHR Perthometr PGK 120 (see Figure 37).

Figure 37. MAHR Perthometr PGK 120 [23]

The samples with lowest wear were examined by surface profiler.

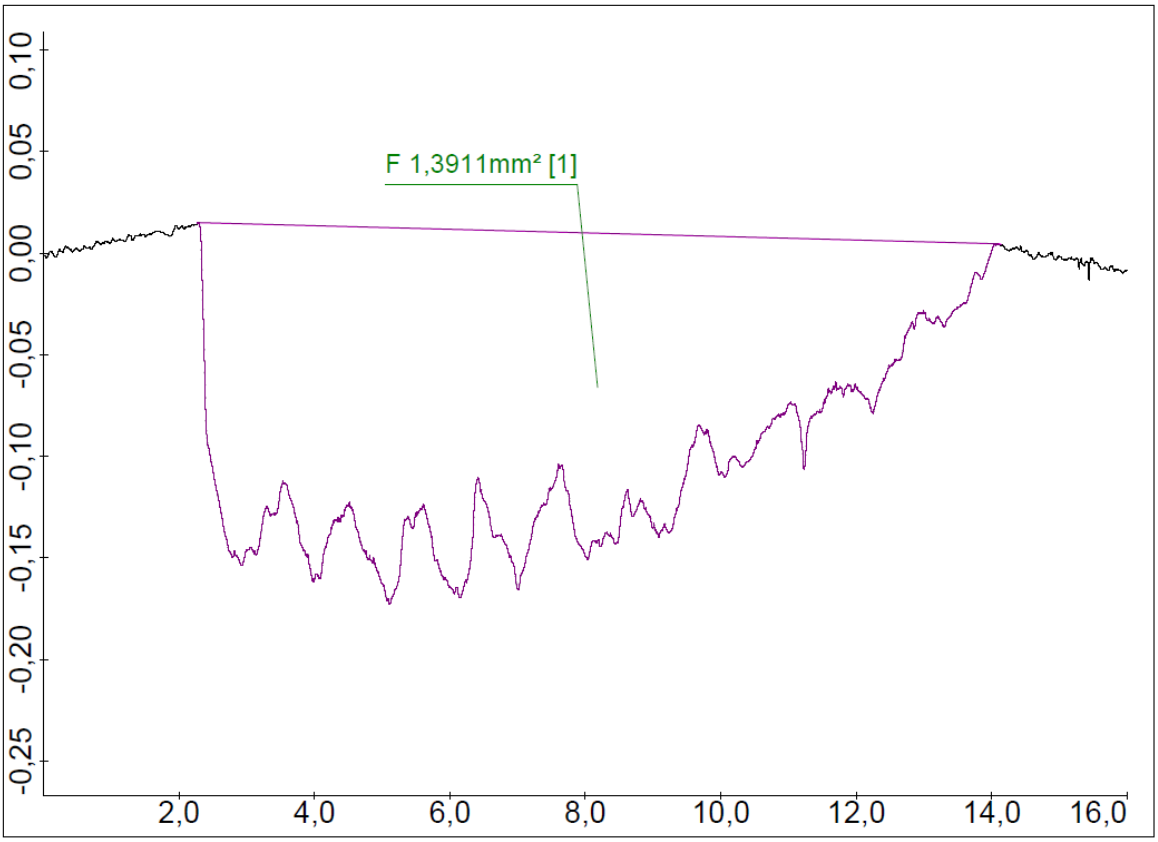


Figure 38. Research result of sample wear 8-12-1 with surface profiler

As we see on Figure 38 the surface profiler gives a 2D profile with depth and width of wear scare. In order to compare the results the average wear depth was found from wear area, using Equation 7.

For instance, average wear depth, calculated by Equation 8 of sample 8-12-1, equals 0.12 mm

$$\frac{1.3911\ mm^2}{11.5\ \text{mm}} = 0.12\ mm$$

Wear depth measured with calipers was equal to 0.11 mm (from Table 13).

6.7 Results comparison, received with a use of surface profiler and calipers

For the data comparison study, the samples exposed to wear by dry wooden wheels without additional load, were chosen. Samples 1, 2, 5 did not participate in research with surface profiler (had depth of wear more than 0.4 mm).

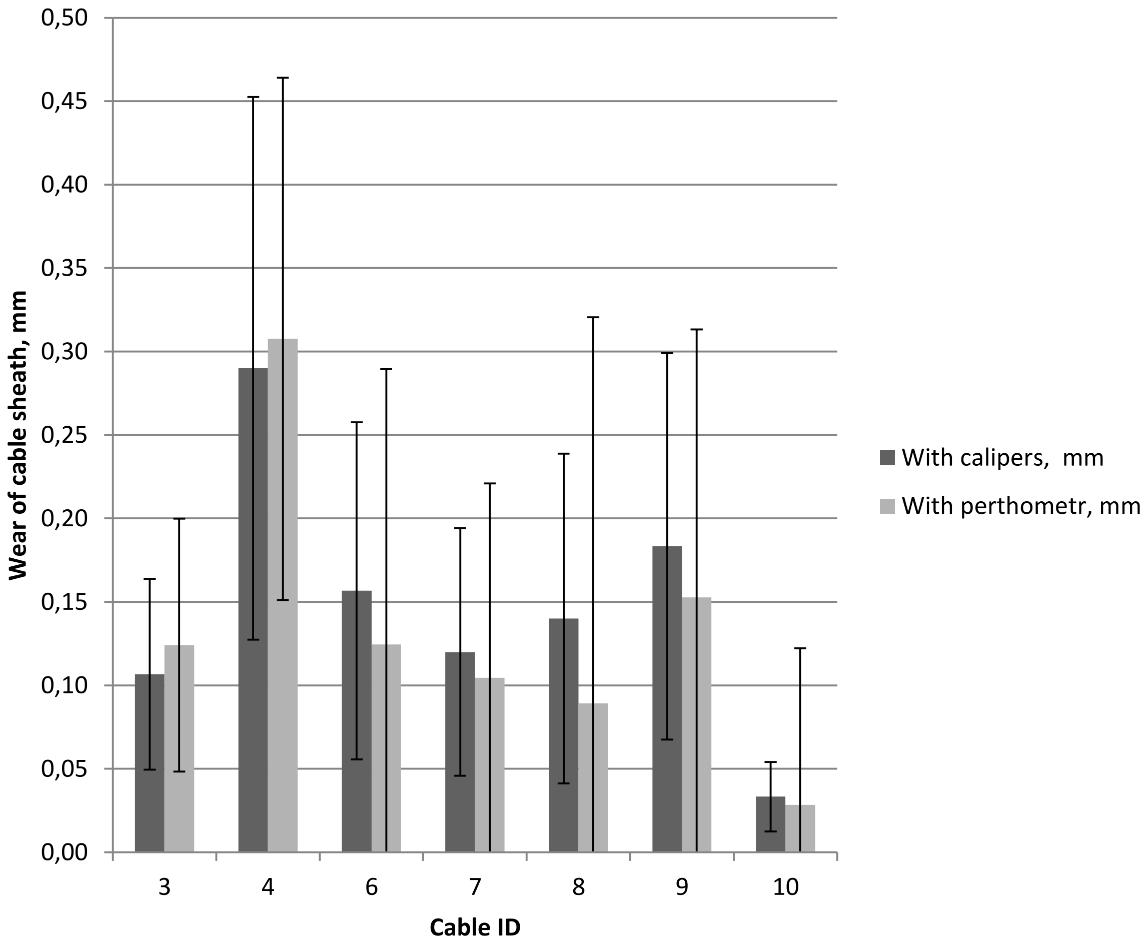


Figure 39. Comparative measurements of research with calipers and surface profiler

As we see from Figure 39, the results of wear examined with a help of calipers are sometimes little bit higher. It is connected to the fact that the cladding wear did not happen evenly that confirmed by data received after using surface profiler

On Figure 40 you can see the research results of unequally worn of sample 7-12-1 with a use of surface profiler

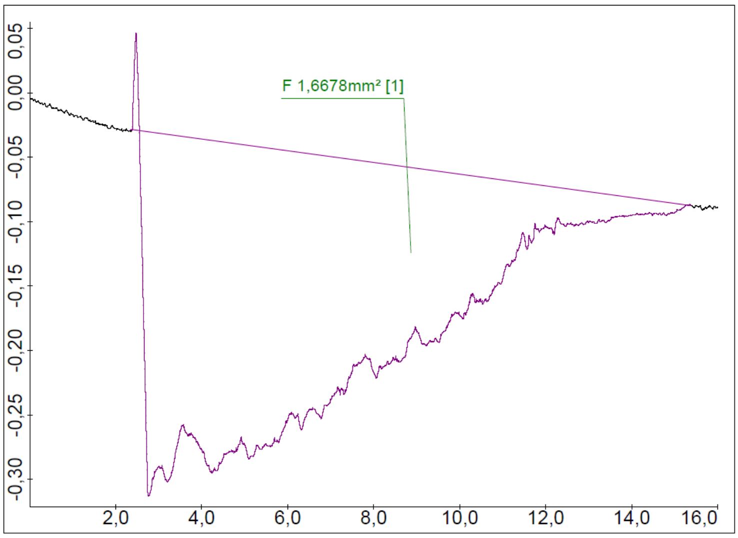


Figure 40. Research results of sample 7-12-1 with a use of surface profiler

As we see on Figure 40 the left part of cladding is worn-out more than the right. It could happen because of a series of reasons. For example: the right side of wheel surface lost a part of its abrasive property, or the surface is smeared by material of cable (reduce friction). Another explanation can be a curved shape of cable.

The difference between measurements by calipers and surface perthometr is given in Table 5.

Table 5. Average wear values (depth) calculated with calipers and surface profiler

Cable	**Calipers mm**	**Perthometr mm**	**Difference mm**
3	0,11	0,12	0,02
4	0,29	0,31	0,02
6	0,16	0,12	-0,03
7	0,12	0,10	-0,02
8	0,14	0,09	-0,05
9	0,18	0,15	-0,03
10	0,03	0,03	0,00

The complete measurements data can be found in APPENDIX 1

CONCLUSION

The purpose of this thesis was to develop the technology of testing and then to test and measure the wear of the covered medium voltage overhead lines conductors sheath after the friction against the wooden and steel wheels.

During the performance of tasks, to improve the level of knowledge on the topic "covered medium voltage overhead lines conductors" as well as "tribology", a lot of literature in English, Estonian and Russian languages was read, which helped to understand better the structure of the cables, to learn about the kinds of sheaths, as well as the materials of which they are made. Once the list of cable sheath construction materials was determined, their properties were studied.

For testing the cable sheaths the Block-on-Ring machine was used. This machine has been chosen for several reasons. For example, the Block-on-Ring machine allows to test simultaneously up to 5 cables. The ability to perform wet tests was also one of the key reasons why this machine has been chosen. Another important reason was that during the tests the machine was available.

A total of 10 cables were selected for testing the cable sheath. They differed from each other by color, diameter, coating material, number of conductors and the manufacturer.

Before the testing of cables began, it was necessary to develop a reusable fixture (cable holder) that was attached to the lever of the Block-on-Ring machine. After it was designed and assembled for fixing the cables themselves were prepared and samples that had a length of 45 mm. This size depends on the Block-On-Ring test machine size (holder and width of wheel).

Testing cables was tested with various parameters. Tests with metal and wooden wheels of varying duration (10 minutes, 120 minutes and 540 minutes) were carried out. Also a number of tests were done with the high load of 10 kg.

During testing of cable sheaths samples, I faced a number of problems that were solved during the work. One of the problems was that the wooden wheels during testing were coated with a layer of polymer sheaths. This polymer layer has diminished the abrasive properties of wooden disks which reduced the wear of cables in subsequent tests.

The problem was solved by machining the surface of the disk with a file 2821-0109 GOST 1465-80 after each test. This method helped to remove the layer of polymer, which covered the wooden wheels after the tests.

Also it was found that already during the 10 minute dry test, wooden wheel got heated as a result, and "melting" as well as the deformation of the shell was discovered on some cable sheaths. The solution was to cool down the wheels after each test.

With steel wheels there were problems associated with rust after wet tests. Adhesion of polymeric film onto steel wheel was also observed. Plaque of rust and layer of polymers were removed mechanically using sandpaper P180 (Buenhler-Met Silicon Carbide grinding paper). The gritness of this grinding paper also possesses necessary qualities. The sand paper was used along with flat metal supporting plate.

The wear of all cable sheaths was measured by calipers. Some samples were also measured by using a surface profiler MAHR Perthometr PGK 120. The results showed that the wear scar surface is not flat after wear. Cables with lowest wear rates were measured by both caliper and perthometr and the results were compared.

The wear results measured by calipers were slightly higher. This was due to the fact that the cable sheath wear does not occur evenly, and using data that was obtained is confirmed by surface profiler.

According to the cable sheath test results, the following conclusions can be made:

- Abrasive properties of wheel decreases with each test carried out and the wear rate of cable decreases.
- The type of test (dry or wet) has an effect on the wear of the cable sheaths. For example, in case of cables 2, 4, 5, 6 the wear during the wet test was higher than during the dry test, while for the cables 1, 3, 7, 8, 9, 10 it was lower during wet test.
- Test duration had an effect on the wear of the wet steel disk. The longer the test, the more the wear.

- Additional loading also affects wear rate of cables, depending on the cable, it increased the wear several times while, however, in case of cables 6 and 10 the effect was minor.
- In the course of all the tests the sheath of the cable number 2 proved to be the worst, and the cables 8 and 9 showed the best results.

It is worth noting that the cable sheath testing helps to choose the cable sheaths with highest resistant against friction. This should lead to increase of reliability of overhead lines and supply of electricity and to reduce the number of accidents caused by falling of trees.

KOKKUVÕTTE

Antud töö eesmärgiks oli kontrollida ja mõõta kaetud õhuliini juhtmete katte kulumist pärast nende hõõrdumist puidu ja terase vastu, koostada katsekehade katsetamise tehnoloogia ja lõpptulemusena testida erinevaid katsekehi.

Etteantud ülesannete täitmiseks ja autori teadmiste taseme tõstmiseks „Kaetud keskpinge õhuliini juhtmed“ ja ka „triboloogia” teemal sai läbi loetud palju materjali nii inglise, eesti kui ka vene keeles. Materjalidega tutvumine aitas paremini mõista kaablite ehitust, saada teavet ümbriskihtide liikidest ja nende valmistamiseks kasutatavatest materjalidest. Pärast kaablite ümbriskihtideks kasutatavate materjalide loetelu välja selgitamist sai uuritud nende omadusi ja kulumist mõjutavaid tegureid.

Kaetud keskpinge õhuliini juhtmete (kaablite) kattekihtide katsetamiseks kasutati modifitseeritud ASTM B611 (plaat vastu ketast) katseseadet. See seade sai välja valitud mitmel erineval põhjustel. Näiteks lubab see seade katsetada samaaegselt viit (5) kaablit. Võimalus teostada märgkatseid oli samuti üheks põhjuseks, miks sai valitud antud katseseade. Vähemtähtis polnud ka see, et antud katsete toimumise ajal polnud seade muude töödega hõivatud.

Teste teostati kokku 10 erinevale kaetud juhtmele (kaabile). Juhtmed erinesid üksteisest värvi, diameetri, kattematerjali, soonte arvu ja tootja poolest.

Enne kaetud keskpinge õhuliini juhtmete (kaablite) katsetamise algust oli vajalik välja töötada mitmekordne hoidik, katsekehade katsemasina külge kinnitamiseks. Pärast kaablite jaoks ettenähtud kinnituse välja töötamist ja kokku panemist valmistati katsekehad, mille pikkuseks oli 45 mm (antud mõõt määrati kindlaks katsemasina mõõtude ja ketaste jämeduse järgi).
Kaablite testimine toimus erinevates keskkondades. Katsed viidi läbi metall- ja puitketastega, erineva kestustega (10 minutit, 120 minutit, 540 minutit). Osades katsetes kasutati ka kõrgendatud, 10-kilogrammist koormust.

Kaablite ümbriskihi katsetel tuli ette rida probleeme, mis õnnestus töö käigus lahendada. Üheks probleemiks oli see, et puitkettad kattusid testi käigus kaablite ümbriskihist pärineva polümeerikihiga. Antud kiht vähendas puitketaste abrasiivomadusi, mistõttu vähenes kulumine järgnevate katsete käigus.

Vältimaks kettale kinnitunud kaabli ümbriskihi mõju järgnevatele katsetele, otsustati peale igat katset töödeda ketaste pinda viiliga 2821-0109 GOST 1465-80. See moodus aitas eemaldada polümeerikihi, mis kattis puitkettaid pärast katset.

Samuti selgus, et juba 10 minutilise kuiva katsetamise käigus toimub puitketta kuumenemine, mille tagajärjel avastati real kaablitel ümbriskihi „sulamine" ja deformatsioon. Lahenduseks oli ketaste jahutamine pärast igat katsetamist.

Probleemid metallketastega olid seotud roostekihiga pärast märga testi, samas kui peale kuiva testi oli märgata polümeerikihi teket. Nii rooste- kui ka polümeerikirme eemaldati mehhaanilisel teel liivapaberi P180 (Buenhler-Met) abil. Selle alla paigaldati metallplaat, et liivapaberi pind oleks paralleelne ketta töödeldava pinnaga.

Kõikide kaablite ümbriskihi kulumist mõõdeti nihikmõõdiku abil. Mõningate kaablite lisamõõtmisel kasutati abivahendina kontaktset profilomeetrit MAHR PGK120. Mõõteseadme tulemused näitasid kulumise pindala ja selleks, et võrrelda nihikmõõdiku ja kontaktse profilomeetri poolt mõõdetud kulumist, oli tarvis arvutada kulumise sügavus.

Nihikmõõdikuga mõõdetud kulumise tulemused olid veidi suuremad. See on seotud sellega, et ümbriskihi kulumine polnud toimunud ühtlaselt ja profilomeetri abil saadud andmed kinnitasid seda.

Kaablite katsetamise tulemuste ja analüüsi põhjal võib teha järgnevad järeldused:

- Ketaste abrasiivomadused vähenevad iga läbiviidud katsega, mistõttu väheneb ka kaablite ümbriskihi kulumine.
- Katse liik (kuiv või märg) mõjutab kaablite ümbriskihi kulumist erinevalt. Nii oli näiteks kaablite Nr 2, 4, 5 ja 6 kulumine märja testi käigus suurem kui kuiva testi puhul, aga kaablitel Nr 1, 3 ja 7-10 vastupidi.
- Katse pikkus mõjub kulumisele. Mida pikem on katse, seda suurem on kulumine.
- Koormuse kasv mõjutab kulumist. Sõltuvalt kaablist suurenes kulumine kordades. Kaablite 6 ja 10 puhul oli kulumine erineva koormusega väga sarnane.

- Läbiviidud katsete jooksul näitas end kõige halvemast küljest kaabel number 2, kõige paremad aga olid kaablid 8 ja 9.

Tasub märkida fakti, et kaetud keskpinge õhuliini juhtmete (kaablite) ümbriskihtide katsetamine aitab valida kulumiskindlamate ümbriskihtidega kaableid. Antud valik aitab suurendada elektrienergia tarnete katkematust ja vähendada elektrilühisest põhjustatud avariisid.

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APPENDIX 1. DATA FROM THE CABLES TESTS

Table 6. Cable 1 data from the tests

	Test type	Diametr mm	Attempt 1 mm	Attempt 2 mm	Attempt 3 mm	Attempt 4 mm	Attempt 5 mm	Attempt 6 mm	Standard deviation	Avarage mm
Cabel 1	Test 1. 10 min dry wood no load	16,0	0,92	0,85	0,37	0,36	0,20	0,17	0,33	0,48
	Test 2. 10 min dry wood no load	16,03	0,50	0,17	0,14				0,20	0,27
	Test 3. 10 min dry wood no load 766rpm	16,03	0,13	0,13					0,00	0,13
	Test 4. 540 min wet wood no load	16,07	0,14							0,14
	Test 6. 120 min wet wood load 10kg	15,75	0,09							0,09
	Test 7. 10 min dry wood no load	16	0,29	0,17					0,08	0,23
	Test 8. 10 min dry steel no load	16	0,31	0,21	0,12				0,10	0,21
	Test 9. 10 min dry wood no load	16	0,22	0,19					0,02	0,21
	Test 10. 10 min dry steel no load	16	0,40	0,10	0,12				0,17	0,21
	Test 11. 10 min wet steel no load	16,02	0,14	0,15	0,08				0,04	0,12
	Test 12. 10 min wet steel load 10kg	16,03	0,50	0,45	0,36				0,07	0,41

Table 7. Cable 2 data from the tests

	Test type	Diametr mm	Attempt 1 mm	Attempt 2 mm	Attempt 3 mm	Attempt 4 mm	Attempt 5 mm	Attempt 6 mm	Standard deviation	Avarage mm
Cabel 2	Test 1. 10 min dry wood no load	15,6	2,7	2,07					0,45	2,39
	Test 2. 10 min dry wood no load	15,6	2,53	2,30	2,15				0,19	2,33
	Test 3. 10 min dry wood no load	15,7	1,63							1,63
	Test 4. 10 min dry wood no load	15,57	1,77	0,91					0,61	1,34
	Test 5. 10 min dry wood no load	15,57	1,27							1,27
	Test 6. 120 min wet wood load 10kg	15,77	0,70							0,70
	Test 7. 540 min wet wood no load	15,73	0,29							0,29
	Test 8. 10 min dry steel no load	15,7	0,31	0,34	0,16				0,10	0,27
	Test 9. 10 min dry steel no load	15,7	0,11	0,12	0,08				0,02	0,10
	Test 10. 10 min wet steel no load	15,7	0,75	0,66	0,67				0,05	0,69
	Test 11. 10 min wet steel no load	15,71	0,28	0,12	0,16				0,08	0,19
	Test 12. 540 min wet steel no load	15,7	1,60							1,60

Table 8. Cable 3 data from the tests

	Test type	Diametr mm	Attempt 1 mm	Attempt 2 mm	Attempt 3 mm	Attempt 4 mm	Attempt 5 mm	Attempt 6 mm	Standard deviation	Avarage mm
Cabel 3	Test 1. 10 min dry wood no load	18,50	0,82	0,67	0,55	0,44	0,40		0,17	0,58
	Test 2. 10 min dry wood no load	18,50	0,22	0,28	0,22	0,13			0,06	0,21
	Test 3. 10 min dry wood no load	18,55	0,08	0,08	0,10				0,01	0,09
	Test 4. 10 min dry wood no load	18,55	0,08							0,08
	Test 5. 540 min wet wood no load	18,59	0,19							0,19
	Test 6. 120 min wet wood load	18,65	0,16							0,16
	Test 7. 10 min wet steel load 10kg	18,52	0,35	0,24	0,18				0,09	0,26
	Test 8. 10 min dry steel no load	18,50	0,08	0,09	0,04				0,03	0,07
	Test 9. 10 min dry steel no load	18,52	0,11	0,08	0,04				0,04	0,08
	Test 10. 10 min wet steel no load	18,58	0,07	0,03	0,017				0,03	0,04

Table 9. Cable 4 data from the tests

	Test type	Diametr mm	Attempt 1 mm	Attempt 2 mm	Attempt 3 mm	Attempt 4 mm	Attempt 5 mm	Attempt 6 mm	Standard deviation	Avarage mm
Cabel 4	Test 1. 10 min dry wood no load	15,70	2,42	1,82					0,42	2,12
	Test 2. 10 min dry wood no load	15,70	1,98	0,64	0,57	0,53			0,70	0,93
	Test 3. 10 min dry wood no load	15,41	0,23							0,23
	Test 4. 10 min dry wood no load	15,41	0,33	0,20	0,14				0,10	0,22
	Test 5. 540 min wet wood no load	15,52	0,15							0,15
	Test 6. 120 min wet wood load	15,23	0,24							0,24
	Test 7. 10 min wet steel load	15,38	0,82	0,83	0,74				0,05	0,80
	Test 8. 10 min wet steel no load	15,37	0,16	0,15	0,10				0,03	0,14
	Test 9. 10 min dry steel no load	15,40	0,15	0,13	0,09				0,03	0,12

Table 10. Cable 5 data from the tests

	Test type	Diametr mm	Attempt 1 mm	Attempt 2 mm	Attempt 3 mm	Attempt 4 mm	Attempt 5 mm	Attempt 6 mm	Standard deviation	Avarage mm
Cabel 5	Test 1. 10 min dry wood no load	16,75	0,9	0,85	0,75				0,08	0,83
	Test 2. 10 min dry wood no load	16,75	0,36	0,27	0,28	0,12			0,10	0,26
	Test 3. 10 min dry wood no load	16,90	0,28	0,11	0,07				0,11	0,15
	Test 4. 540 min wet wood no load	16,71	0,20							0,20
	Test 5. 120 min wet wood load 10kg	16,71	0,08							0,08
	Test 6. 10 min wet wood load 10kg	16,92	0,32	0,26	0,25				0,04	0,28
	Test 7. 10 min wet steel no load	16,58	0,29	0,15	0,16				0,08	0,20
	Test 8. 10 min dry steel no load	16,70	0,06	0,04	0,03				0,02	0,04

Table 11. Cable 6 data from the tests

	Test type	Diametr mm	Attempt 1 mm	Attempt 2 mm	Attempt 3 mm	Attempt 4 mm	Attempt 5 mm	Attempt 6 mm	Standard deviation	Avarage mm
Cabel 6	Test 1. 10 min dry wood no load	15,00	1,92	1,81					0,08	1,87
	Test 2. 10 min dry wood no load	15,00	1,93	1,79	1,65				0,14	1,79
	Test 3. 10 min dry wood no load	15,00	0,98	0,9	0,74				0,12	0,87
	Test 4. 10 min dry wood no load	14,92	0,27	0,2	0,13	0,06			0,09	0,17
	Test 5. 540 min wet wood no load	15,00	0,24	0,11					0,09	0,18
	Test 6. 120 min wet wood load 10kg	15,00	0,08							0,08
	Test 7. 10 min wet steel load 10kg	14,84	0,15	0,13	0,09				0,03	0,12
	Test 8. 10 min wet steel no load	15,00	0,17	0,07	0,11				0,05	0,12
	Test 9. 10 min dry steel no load	15,00	0,12	0,03	0,06				0,05	0,07

Table 12. Cable 7 data from the tests

	Test type	Diametr mm	Attempt 1 mm	Attempt 2 mm	Attempt 3 mm	Attempt 4 mm	Attempt 5 mm	Attempt 6 mm	Standard deviation	Avarage mm
Cabel 7	Test 1. 10 min dry wood no load	14,00	1,14	0,98	1,04				0,08	1,05
	Test 2. 10 min dry wood no load	14,00	0,24	0,15	0,11	0,08			0,07	0,15
	Test 3. 10 min dry wood no load	13,87	0,17	0,13	0,06				0,06	0,12
	Test 4. 540 min wet wood no load	14,00	0,18	0,15					0,02	0,17
	Test 5. 120 min wet wood load 10kg	13,93	0,18							0,18
	Test 6. 10 min wet steel load 10kg	13,80	0,66	0,34	0,13				0,27	0,38
	Test 7. 10 min wet steel no load	13,90	0,13	0,08	0,04				0,05	0,08
	Test 8. 10 min dry steel no load	13,92	0,18	0,12	0,11				0,04	0,14

Table 13. Cable 8 data from the tests

	Test type	Diametr mm	Attempt 1 mm	Attempt 2 mm	Attempt 3 mm	Attempt 4 mm	Attempt 5 mm	Attempt 6 mm	Standard deviation	Avarage mm
Cabel 8	Test 1. 10 min dry wood no load	16,00	0,18	0,22	0,12	0,16			0,04	0,17
	Test 2. 10 min dry wood no load	15,92	0,08	0,11	0,07				0,02	0,09
	Test 3. 540 min wet wood no load	16,00	0,08	0,08					0,00	0,08
	Test 5. 10 min wet steel load 10kg	15,77	0,35	0,34	0,22				0,07	0,30
	Test 6. 10 min wet steel no load	15,80	0,08	0,06	0,05				0,02	0,06
	Test 7. 10 min dry steel no load	15,90	0,16	0,08	0,10				0,04	0,11
	Test 8. 10 min dry steel no load	16,00	0,03	0,02	0,03				0,01	0,03

Table 14. Cable 9 data from the tests

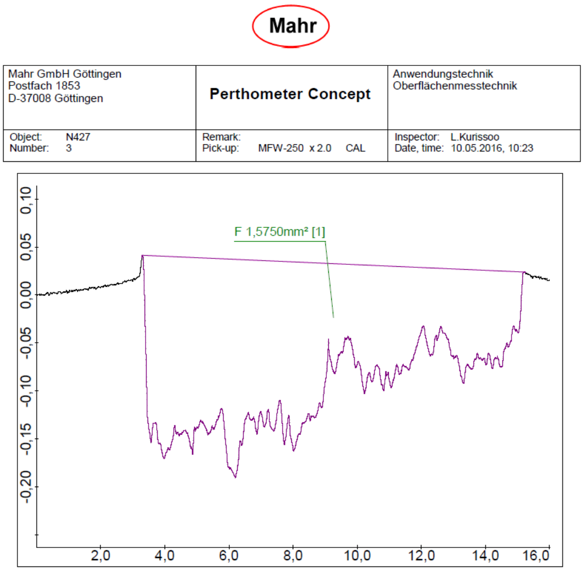
	Test type	Diametr mm	Attempt 1 mm	Attempt 2 mm	Attempt 3 mm	Attempt 4 mm	Attempt 5 mm	Attempt 6 mm	Standard deviation	Avarage mm
Cabel 9	Test 1. 10 min dry wood no load	15,44	0,21	0,13	0,20				0,04	0,18
	Test 2. 10 min dry wood no load	15,40	0,11	0,05					0,04	0,08
	Test 3. 10 min dry wood no load	15,40	0,15	0,10	0,13	0,02			0,06	0,10
	Test 3. 10 min dry wood no load	15,40	0,08	0,12					0,03	0,10
	Test 4. 540 wet wood no load	15,34	0,07							0,07
	Test 4. 540 wet wood no load	15,34	0,07							0,07
	Test 6. 120 wet steel load 10kg	15,40	1,00							1,00
	Test 7. 10 min wet steel load 10kg	15,17	0,32	0,33	0,11				0,12	0,25
	Test 8. 10 min wet steel	15,29	0,09	0,08	0,03				0,03	0,07
	Test 9. 540 min wet steel no load	15,40	1,32	1,15					0,12	1,26
	Test 10. 10 dry steel no load	15,22	0,12	0,13	0,09				0,02	0,11

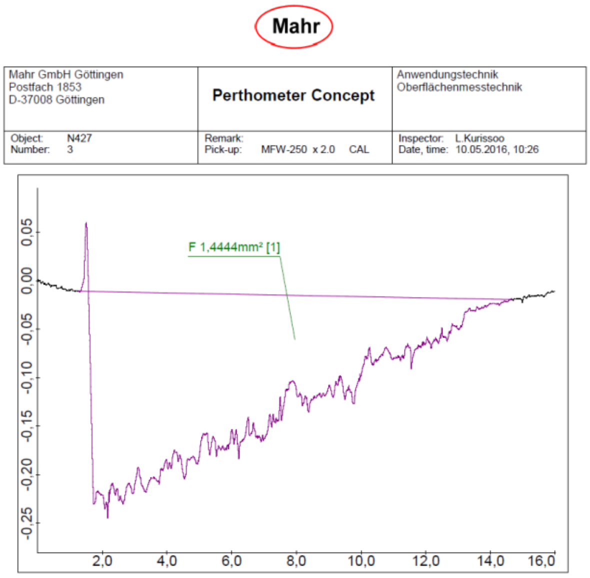
Table 15. Cable 10 data from the tests

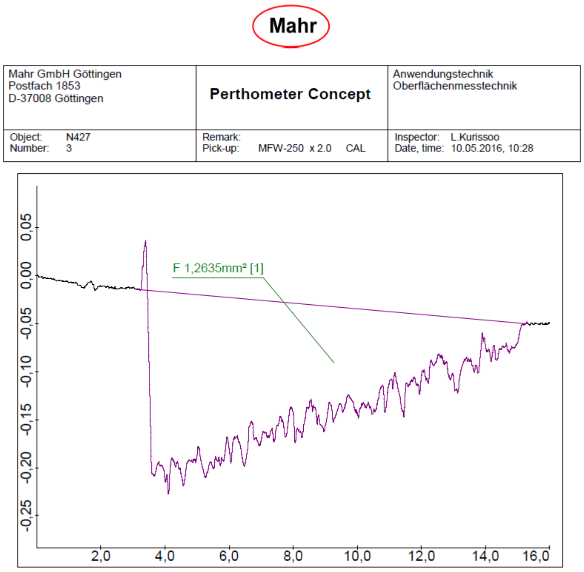
`	Test type	Diametr mm	Attempt 1 mm	Attempt 2 mm	Attempt 3 mm	Attempt 4 mm	Attempt 5 mm	Attempt 6 mm	Standard deviation	Avarage mm
Cabel 10	Test 1. 10 min dry wood no load	14,50	1,11	0,83	0,36				0,38	0,77
	Test 2. 10 min dry wood no load	14,50	0,43	0,46	0,39	0,21			0,11	0,37
	Test 3. 10 min dry wood no load	14,63	0,05	0,12	0,04				0,04	0,07
	Test 4. 120 min wet steel load 10kg	14,35	0,66							0,66
	Test 5. 10 min wet steel no load	14,40	0,15	0,10	0,07				0,04	0,11
	Test 6. 10 min wet steel load 10kg	14,39	0,08	0,12	0,06				0,03	0,09
	Test 7. 540 min wet steel no load	14,70	0,45							0,45
	Test 8. 540 min wet wood no load	14,50	0,17							0,17
	Test 9. 10 min dry steel no load	14,50	0,32	0,06	0,05				0,15	0,14

APPENDIX 2. PERTHOMETR DATA FROM TESTS AGAINST DRY WOODEN WHEEL WITH LOAD OF 2.5 KG TESTS

A.2.1 Cable 3 perthometr data from tests against dry wooden wheel with load of 2.5 kg tests



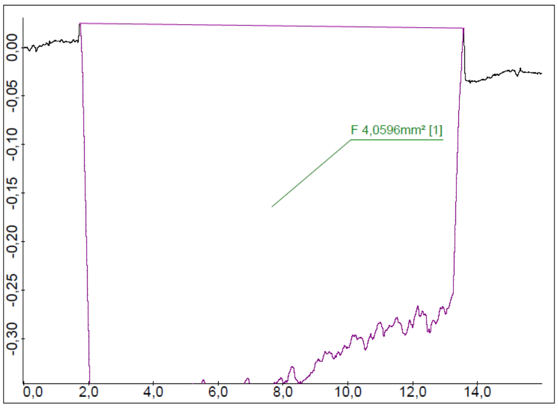




A.2.2 Cable 4 perthometr data from tests against dry wooden wheel with load of 2.5 kg tests

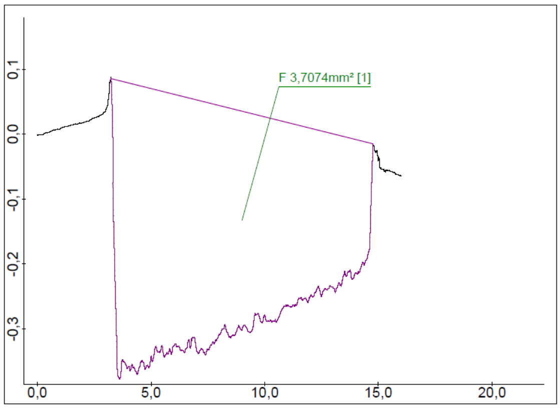
Mahr

Mahr GmbH Göttingen Postfach 1853 D-37008 Göttingen	**Perthometer Concept**	Anwendungstechnik Oberflächenmesstechnik
Object: N427 Number: 3	Remark: Pick-up: MFW-250 x 2.0 CAL	Inspector: L.Kurissoo Date, time: 10.05.2016, 09:49



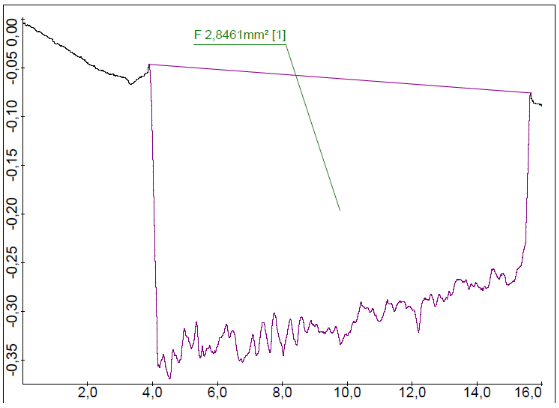
Mahr

Mahr GmbH Göttingen Postfach 1853 D-37008 Göttingen	**Perthometer Concept**	Anwendungstechnik Oberflächenmesstechnik
Object: N427 Number: 3	Remark: Pick-up: MFW-250 x 2.0 CAL	Inspector: L.Kurissoo Date, time: 10.05.2016, 09:53

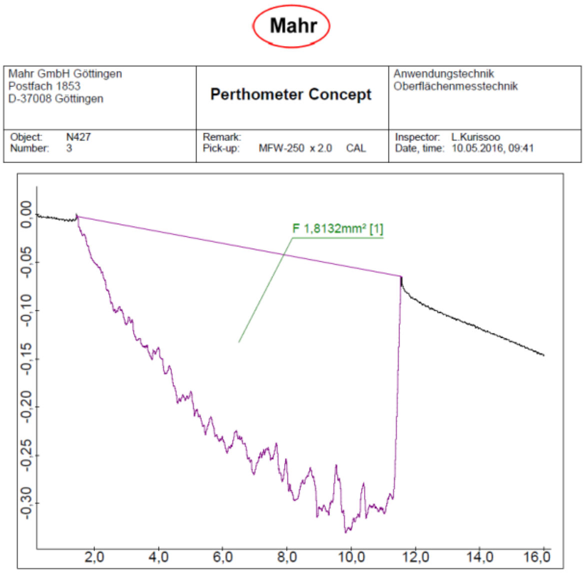


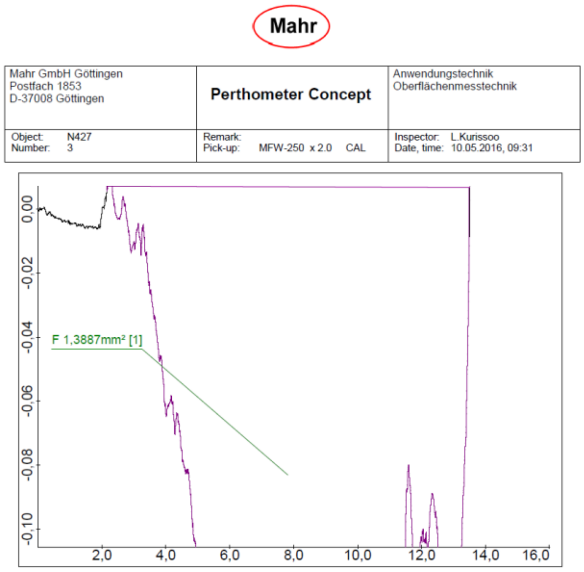
Mahr

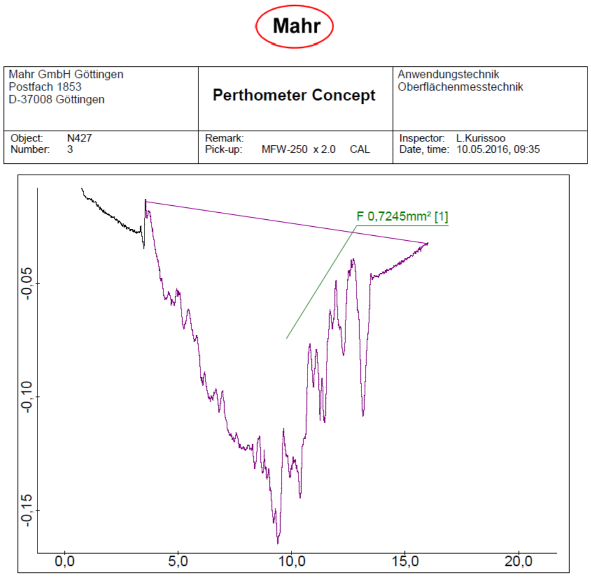
Mahr GmbH Göttingen Postfach 1853 D-37008 Göttingen	**Perthometer Concept**	Anwendungstechnik Oberflächenmesstechnik
Object: N427 Number: 3	Remark: Pick-up: MFW-250 x 2.0 CAL	Inspector: L.Kurissoo Date, time: 10.05.2016, 09:46



A.2.3 Cable 6 perthometr data from tests against dry wooden wheel with load of 2.5 kg tests







A.2.4 Cable 7 perthometr data from tests against dry wooden wheel with load of 2.5 kg tests

Mahr GmbH Göttingen Postfach 1853 D-37008 Göttingen	Perthometer Concept	Anwendungstechnik Oberflächenmesstechnik
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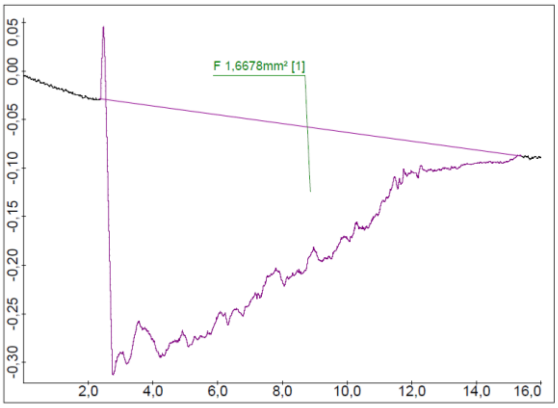

Mahr GmbH Göttingen Postfach 1853 D-37008 Göttingen	Perthometer Concept	Anwendungstechnik Oberflächenmesstechnik
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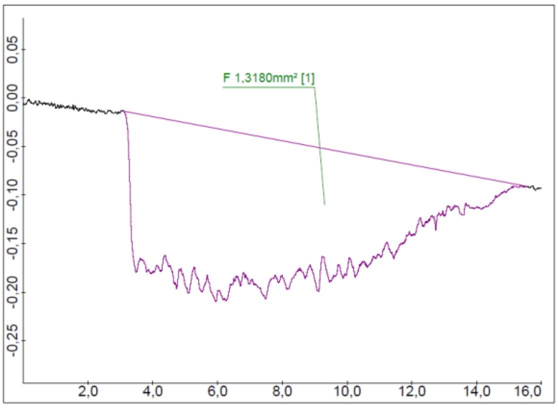
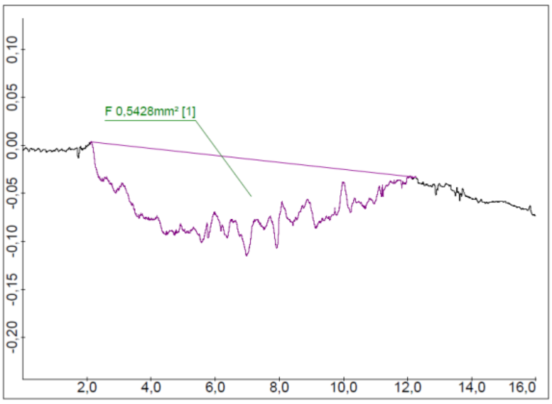
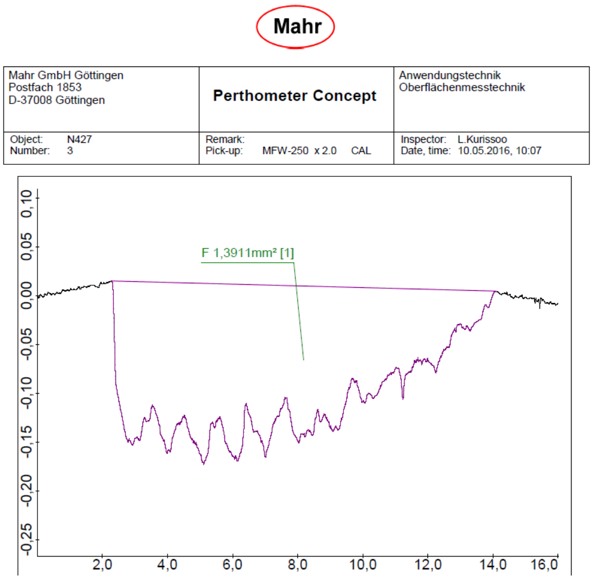
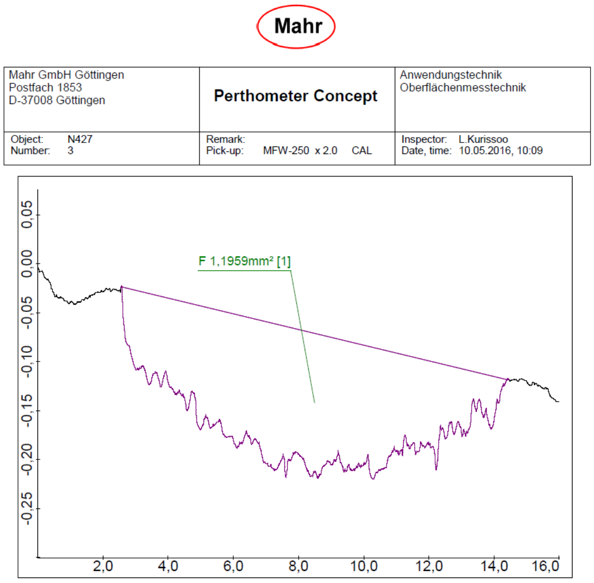


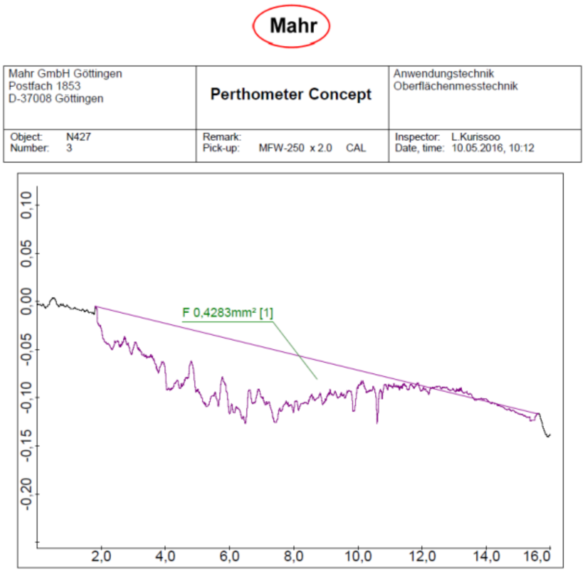
Mahr GmbH Göttingen Postfach 1853 D-37008 Göttingen	Perthometer Concept	Anwendungstechnik Oberflächenmesstechnik
Object: N427 Number: 3	Remark: Pick-up: MFW-250 x 2.0 CAL	Inspector: L.Kurissoo Date, time: 10.05.2016, 10:21



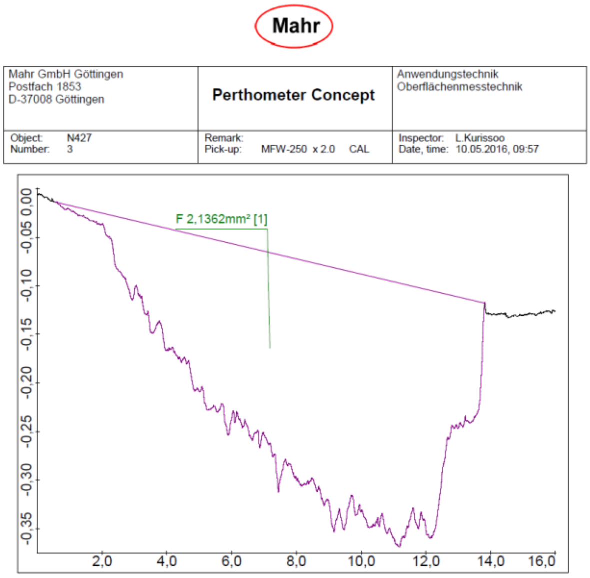
A.2.5 Cable 8 perthometr data from tests against dry wooden wheel with load of 2.5 kg tests

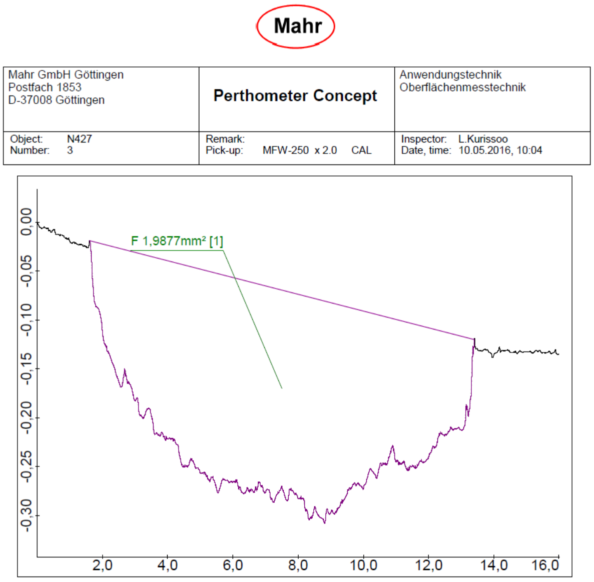


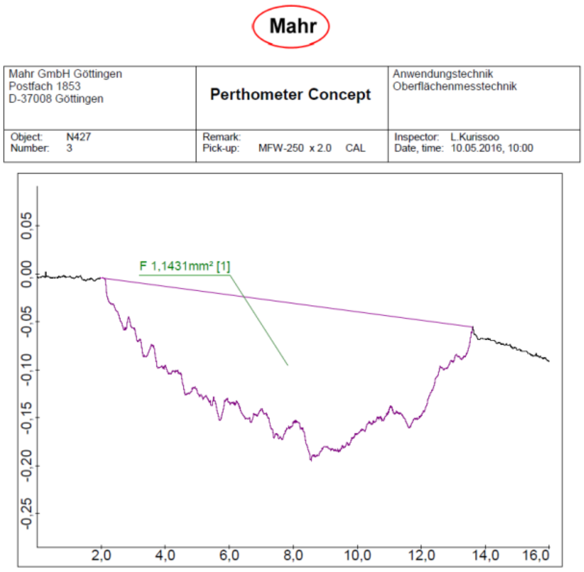




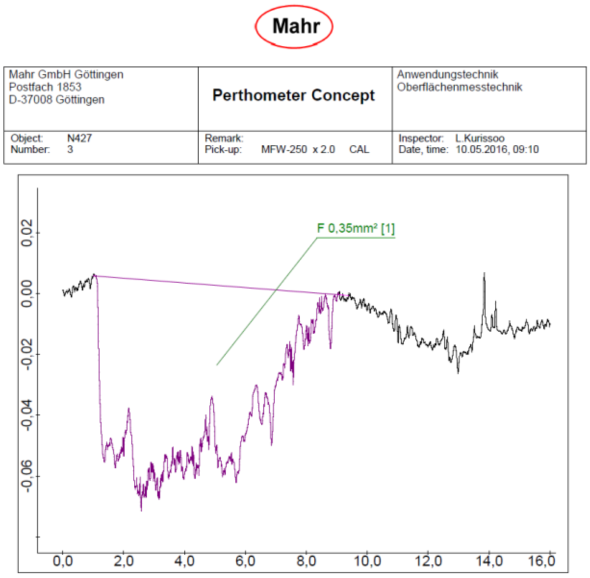
A.2.6 Cable 9 perthometr data from tests against dry wooden wheel with load of 2.5 kg tests

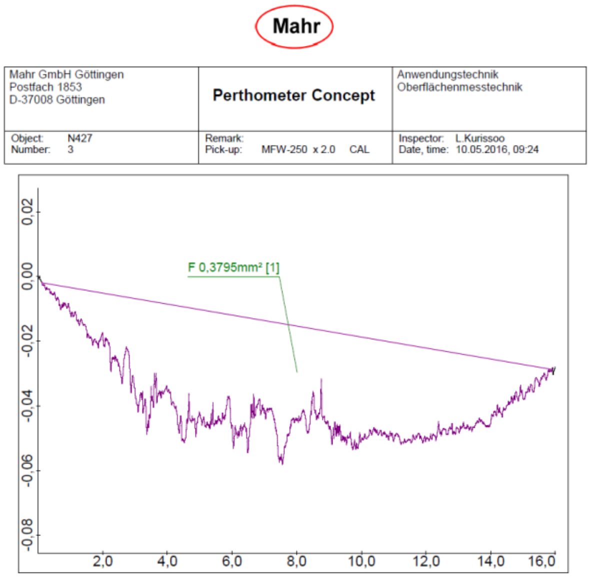


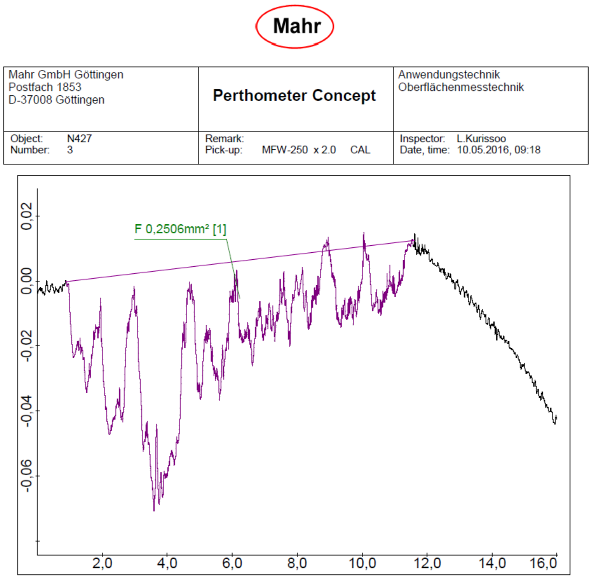




A.2.7 Cable 10 perthometr data from tests against dry wooden wheel with load of 2.5 kg tests







APPENDIX 3. MEASUREMENT DATA OF WEAR FROM CALIPERS AND SURFACE PROFILER (10 MINUTE TEST WITH DRY WOODEN WHEELS WITH LOAD OF 2.5 KG)

Table 16. Measurement data of wear from calipers (10 minute test with dry wooden wheels without additional load)

Cabel ID	Calipers 1 mm	Calipers 2 mm	Calipers 3 mm	Avarage mm
3	0,13	0,11	0,08	0,11
4	0,35	0,27	0,25	0,29
6	0,2	0,14	0,13	0,16
7	0,17	0,13	0,06	0,12
8	0,12	0,16		0,14
9	0,2	0,23	0,12	0,18
10	0,05	0,03	0,02	0,03

Table 17. Measurement data of wear area from surface profiler (10 minute test with dry wooden wheels without additional load)

Cabel ID	Perthometr 1 mm^2	Perthometr 2 mm^2	Perthometr 3 mm^2
3	1,58	1,44	1,26
4	4,06	3,71	2,85
6	1,81	1,39	0,72
7	1,67	1,32	0,54
8	1,39	1,20	0,43
9	2,14	1,99	1,14
10	0,35	0,38	0,25

Table 18. Measurement data of wear lenght from surface profiler (10 minute test with dry wooden wheels without additional load)

Cabel ID	Wear length 1 mm	Wear length 2 mm	Wear length 3 mm
3	11,5	11,5	11,5
4	11,5	11,5	11,5
6	10	11	11
7	11,5	11,5	10
8	11,5	11,5	10
9	11,5	11,5	11,5
10	11,5	11,5	11,5

Table 19. Calculated wear depth using data from Table 17 and Table 18

Cabel ID	Wear depth 1 mm	Wear depth 2 mm	Wear depth 3 mm	Avarage mm
3	0,14	0,13	0,11	0,12
4	0,35	0,32	0,25	0,31
6	0,18	0,13	0,07	0,12
7	0,15	0,11	0,05	0,10
8	0,12	0,10	0,04	0,09
9	0,19	0,17	0,10	0,15
10	0,03	0,03	0,02	0,03