Part 3.2: Rope friction tests: Rope on portcullis

Chuyen K.L. Nguyen, Uwe E. Dorka

Contents

Purpose of investigation

During the first tests on the antechamber replica, it became immediately clear that the friction occurring between ropes and portcullises at the entry and exit points (fig. 1) played a major role in the development of the forces. It was noted that, wear on the ropes was mainly produced at these corners. Therefore, a series of tests was devised to study the friction between rope and portcullis at these locations in detail.

Lubricants based on animal fat or plant oils were available at the time of Cheops and may have been used to reduce wear on the ropes and enable a smoother operation. Therefore, we also studied the effect of different lubricants on this "corner friction".

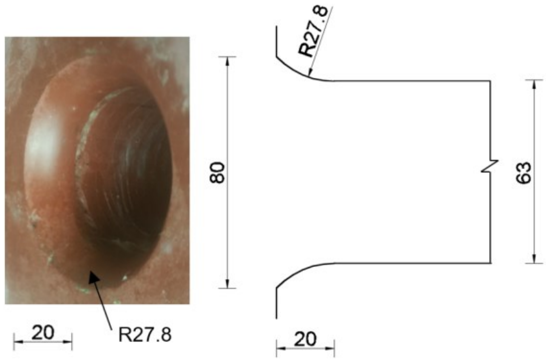


Fig. 1. Entrance to a hole in the portcullis replicas. The edges were smoothed prior to testing with a grinding stone. Dimension are in mm. (photo by S. Schuster)

Test setup

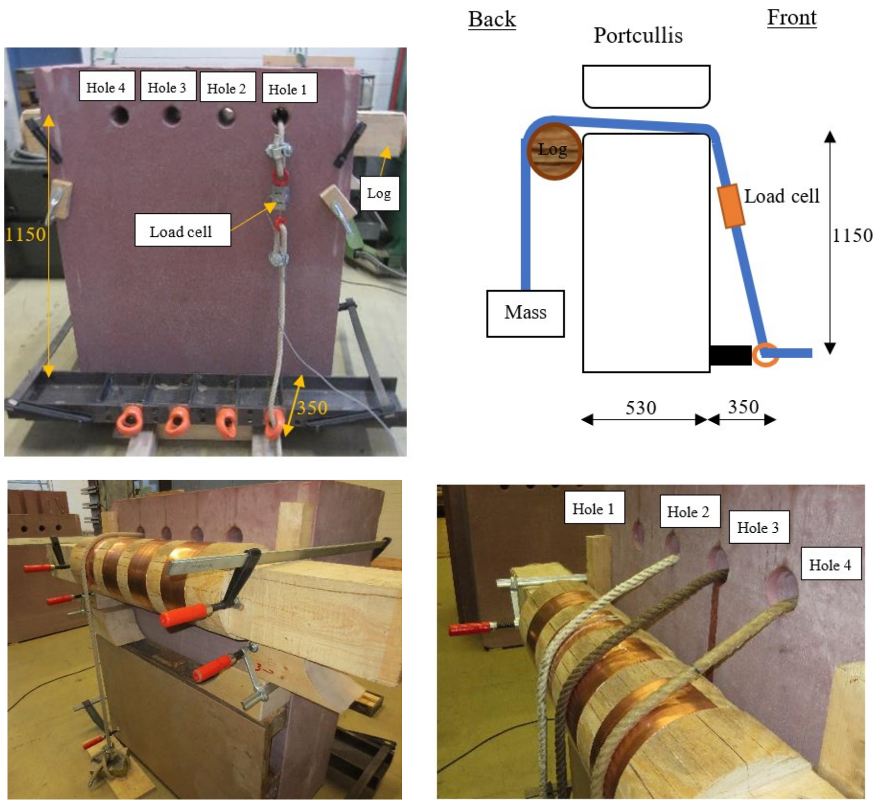


Fig 2. Test setup. Front and principle (top). Log placing on the back for 1- and 2-corner contacts (bottom left and right). Ropes had an angle of about 45° for the 2-corner contact. Dimension are in mm. (photos by S. Schuster)

When lowering the portcullises, the ropes were in contact with either one or both of these corners. We therefore devised a test setup that allowed to study 1-corner and 2-corner contacts (fig. 2).

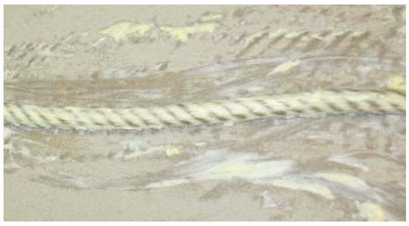
The ropes were pulled and released through the red hoops at the front (fig. 2 top left). A mass of 13.38 kg was attached in the back. Together with connectors and part of the rope, the total mass amounted to 15 kg. A load cell measured the force in the ropes after exiting the portcullis at the front. (fig. 2, top left).

Materials

Ropes and portcullises were the same as reported in part 1.

Lubricants were selected based on possible availability at the time of Cheops. These were animal fats and plant oils. There is little variance in lubrication properties between various animal fats or plant oils[1]. Therefore, we could select regular butter and rapeseed oil representing typical animal fats and plant oils respectively. We also selected a performance grade modern lubricant (Molykote PG-75) for comparison. The properties of the lubricants and their application to the ropes are given in Tab 1. Butter and Molykote PG-75 were applied by hand, rapeseed oil by drenching.

Tab 1. Properties and application of lubricants. (1 cP = 10^{-2} P = 10^{-3} Pa*s, kinematic viscosity = dynamic viscosity / density) (photo by S. Schuster)

Lubricant	Lubrication properties	Application to ropes
Animal fat: butter[2]	density: 911 kg/m^3 dynamic viscosity: 42 cP [3] kinematic viscosity at 43° C: 46 mm^2/s	
Plant oil: rapeseed oil[4]	density: 914.5 kg/m^3 kinematic viscosity at 40° C: 34.06 mm^2/s [5]	
Performance grade: Molykote PG-75[6]	density: 860 kg/m^3 kinematic viscosity at 40° C: 32 mm^2/s [7]	

[1] Fernando (2006)
[2] Approximate Viscosities of Some Common Liquids
[3] DIN 1342-2
[4] Esteban (2012)
[5] DIN 51605
[6] Product Information Molykote PG-75
[7] DIN 51562

Measurement and data processing system

The forces in the ropes were measured with high-resolution load cells (Hottinger Baldwin HBMS9/S9M, range +/- 10 kN, resolution +/- 2 N) in the setting shown in fig 1.

The loadcells were connected to an Autolog 3000[8] system from Peekel. The raw data was sampled with 100 points/sec and calibrated to represent the forces in Newton. Data were sent to the computer where the measurements of each test were stored in a separate file. Using the program LabVIEW Version 2015[9] from National Instruments, the raw data was processed according to fig 3. Real-time charts of the processed data were available during testing and allowed immediate interpretation and actions.

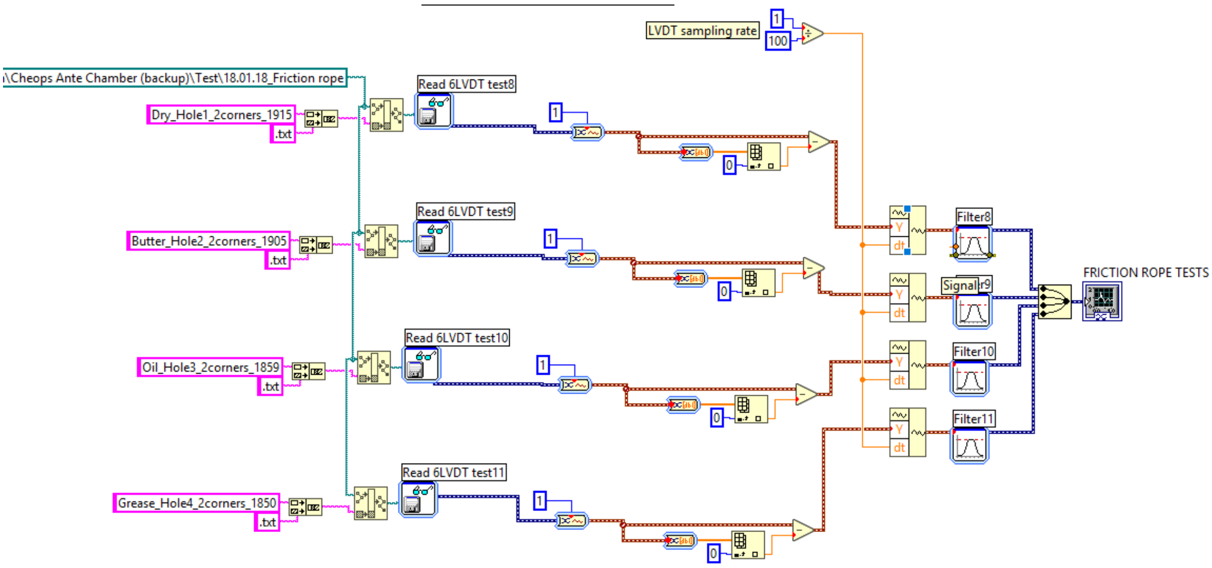


Fig 3. Labview process used for force measurement and data processing. The sampling rate was 100 Hz. A Butterworth filter was applied with 0-1 Hz cut-off frequencies.

Testing program and process

Table 2. provides the testing program with variations on lubricants for the 1-corner and 2-corner contacts. Because the lubricants soiled the holes, care was taken to avoid mixing lubricants when placing the ropes.

Tab 2. Testing program. See fig. 2 for location of holes.

Test no.	Contact type	Lubricant	Hole	Data file
1	1-corner	dry	1	Dry_Hole1_1corner_1744.txt
2			2	Dry_Hole2_1corner_1726.txt
3			3	Dry_Hole3_1corner_1732.txt
4			4	Dry_Hole4_1corner_1738.txt
5		butter	2	Butter_Hole2_1corner_1821.txt
6		oil	3	Oil_Hole3_1corner_1829.txt
7		PG-75	4	Grease_Hole4_1corner_1838.txt
8	2-corner	PG-75	4	Grease_Hole4_2corners_1850.txt
9		oil	3	Oil_Hole3_2corners_1859.txt
10		butter	2	Butter_Hole2_2corners_1905.txt
11		dry	1	Dry_Hole1_2corners_1915.txt

[8] Autolog 3000 Specification
[9] Labview V 2015

The testing process was as follows: First, the mass was lifted just above the floor to tension the rope. Then, the rope was pulled for 2-3 seconds, moving it about 300 mm across the contact points. After holding it for another 2-3 seconds, the rope was released with the same speed until the mass almost touched the floor. This pull-and-release process (PAR) was repeated three times. The forces were measured from start to finish.

Test results

The load cell measurements are given for all tests in fig. 4 (non-lubricated), fig. 5 (1-corner contact and fig. 6 (2-corner contact).

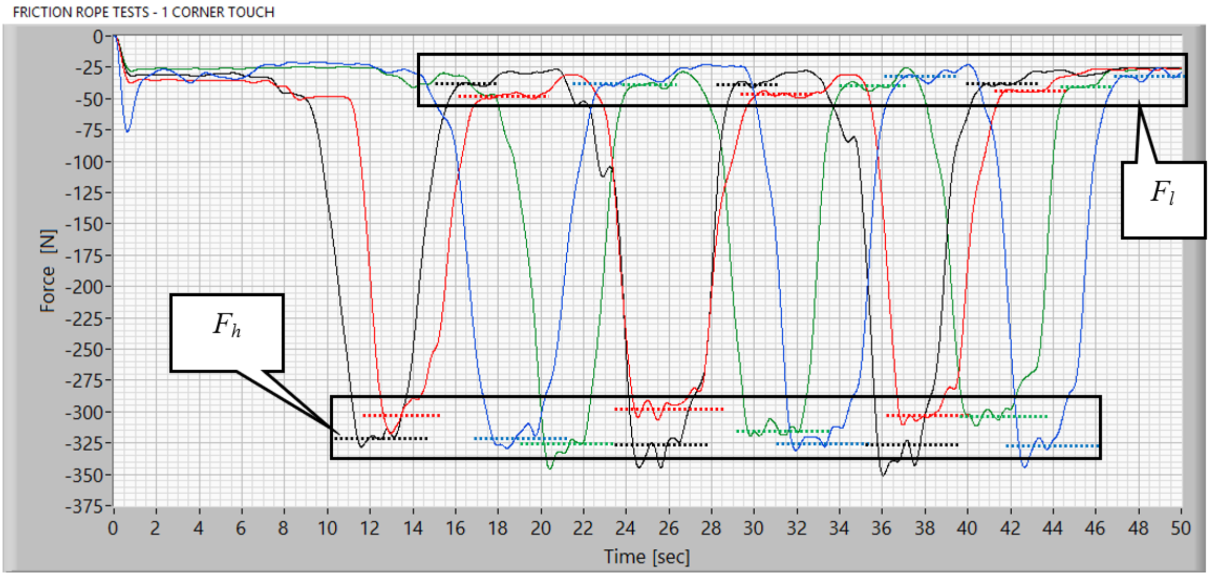


Fig. 4. 1-corner contact: dry, hole 1 (blue), hole 2 (red), hole 3 (black) hole 4 (green), tests 1-4.

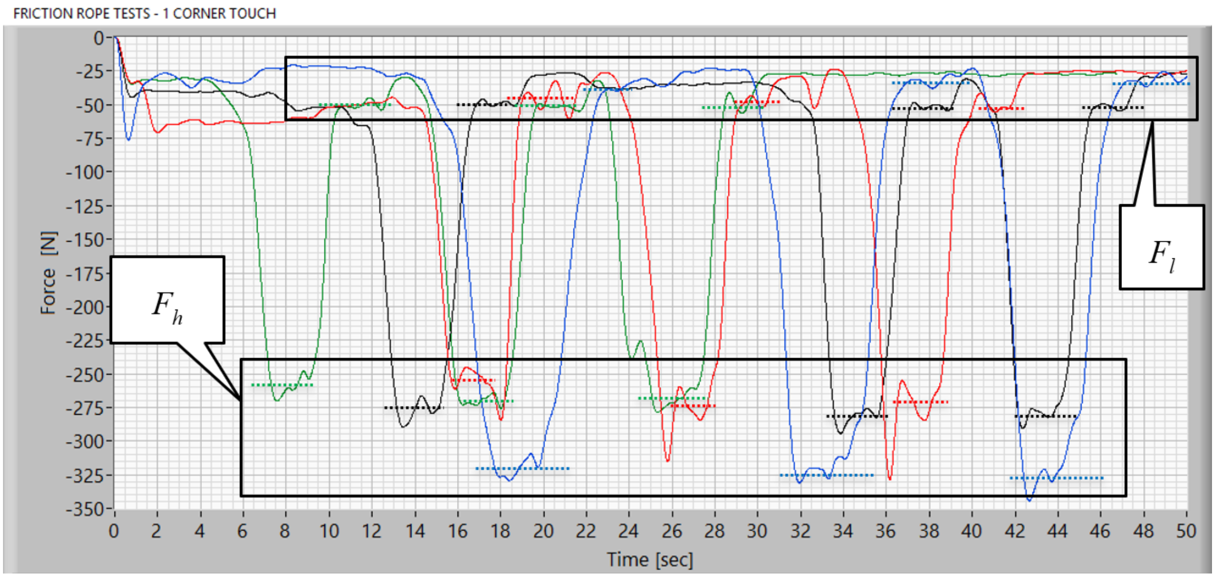


Fig. 5. 1-corner contact: dry (blue), butter (red), oil (black) and PG-75 (green), tests 1 and 5-7.

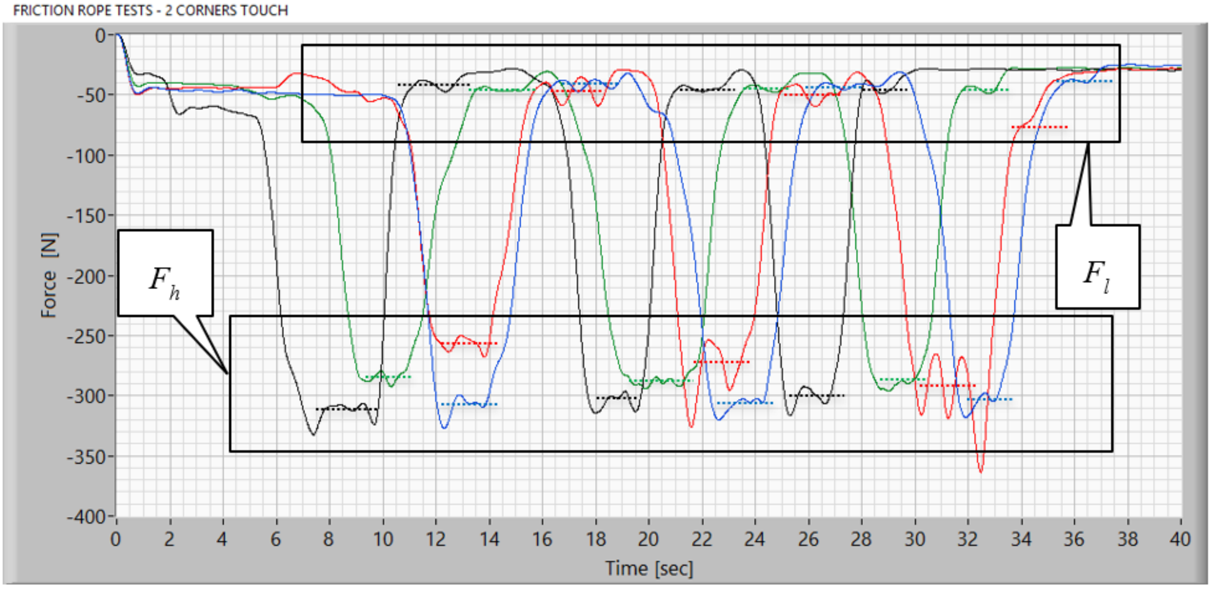


Fig. 6. 2-corner contact: dry (blue), butter (red), oil (black) and PG-75 (green), tests 7-10.

The three PARs (pull-and-release processes) can be clearly identified for all tests with a high force F_h associated with pulling and a low force F_l with releasing.

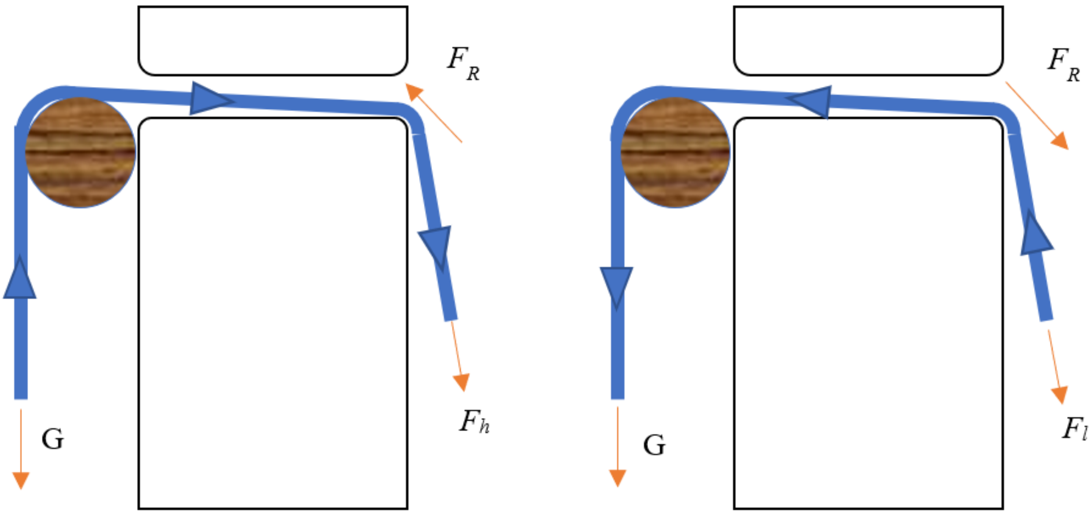


Fig 7. Forces acting on the rope during a PAR when pulling (left) and releasing (right). 1-corner contact. Blue arrows indicate direction of motion. Friction between rope and copper plate on the log is negligible.

Fig. 7 illustrates the forces acting on the rope during a PAR, where the friction force always counters the motion and thus changes direction between pulling and releasing. This provides the following relationships:

$$F_h = G + F_R \qquad \text{for pulling,}$$

$$F_l = G - F_R \qquad \text{for releasing.}$$

Thus, F_R can be calculated from the measurements by

$$F_R = (F_h - F_l)/2$$

and the coefficient of friction μ is given by

$$\mu = F_R / G, \text{ with } G = 150 \text{ N.}$$

Forces F_l and F_h can be taken from the measurements in an average sense for each PAR, as indicated in figs. 4-6 to calculate F_R and μ. The results are presented in tab. 3.

Tab 3. F_l, F_h, F_R (in N) and μ for all PARs

	1st PAR				2nd PAR				3rd PAR			
	F_l	F_h	F_R	μ	F_l	F_h	F_R	μ	F_l	F_h	F_R	μ
1-corner contact												
Dry	35.0	320.0	142.5	0.95	35.0	320.0	142.5	0.95	35.0	320.0	142.5	0.95
	50.0	305.0	127.5	0.85	47.0	300.0	126.5	0.84	45.0	305.0	130.0	0.87
	40.0	320.0	140.0	0.93	40.0	325.0	142.5	0.95	40.0	325.0	142.5	0.95
	40.0	320.0	140.0	0.93	40.0	325.0	142.5	0.95	40.0	325.0	142.5	0.95
Butter	45.0	265.0	110.0	0.73	49.0	273.0	112.0	0.75	53.0	270.0	108.5	0.72
Oil	50.0	275.0	112.5	0.75	54.0	281.0	113.5	0.76	53.0	282.0	114.5	0.76
PG-75	50.0	258.0	104.0	0.69	52.0	270.0	109.0	0.73	51.0	262.0	105.5	0.70
2-corner contact												
Dry	45.0	312.5	133.8	0.89	45.0	312.5	133.8	0.89	30.0	310.0	140.0	0.93
Butter	50.0	260.0	105.0	0.70	50.0	290.0	120.0	0.80	30.0	315.0	142.5	0.95
Oil	40.0	320.0	140.0	0.93	45.0	305.0	130.0	0.87	45.0	303.5	129.3	0.86
PG-75	45.0	285.0	120.0	0.80	45.0	290.0	122.5	0.82	40.0	291.5	125.8	0.84

Observations

Dry μ is stable at 0.92 average for the 1-corner contact. It is observed though that test 2 (line 2 in tab. 3) has an unusually low average of 0.85 and that the dry 2-corner contact is slightly lower (0.90) than the 1-corner contact. This demonstrates a greater variability under dry conditions when compared to the lubricated cases.

μ resulting from butter is stable for the 1-corner contact with an average of 0.73 but increases with PARs in the 2-corner tests from 0.70 to 0.95 due to some damage. This may be explained by the fact that a better protection of the strands and fibres is only achieved when the butter can melt into them. This did not occur in these tests but was observed during the experiments on the portcullises.

μ resulting from oil was stable for the 1-corner contact with an average of 0.76 and for the 2-corner contact at 0.90. This stability was due to full penetration when the rope was drenched.

As expected, μ resulting from PG-75 had the lowest values. It had a stable average of 0.71 for the 1-corner and 0.82 for the 2-corner tests. PG-75 easily penetrated the rope allowing its superior lubrication properties coming to bear.

With an average of 0.92, μ for dry friction is much larger when compared to standard tests[10], where it is in the order of 0.09 for plant oils and animal fats alike. Lubrication reduces the average value for the 1-corner contact to 0.73 (butter), 0.76 (oil) and 0.71 (PG-75) but is still very large.

This can be explained by mechanisms occurring in the cases of "corner friction", where a very strong point-deformation takes place in the rope. This produces not only the usual surface friction (which becomes almost negligible), but foremost activates local resistance within the rope by twisting strands against each other and shearing, even rupturing fibres.

Lubricants creep between the strands and even penetrate into the fibres, which allows the strands and fibres to move more easily against each other, thus reducing the resistance against local rope deformations. They also reduce the surface friction, of course.

With little difference between μ for butter (0.73), oil (0.76) and PG-75 (0.75) in the 1-corner contact, Cheops' scribe engineers had an easy-to-apply, high-end lubricant at their disposal: butter!

[10] Fernando (2006)

References

Approximate Viscosities of Some Common Liquids. https://www.michael-smith-engineers.co.uk/resources/useful-info/approximate-viscosities-of-common-liquids-by-type [Accessed on 09.07.2020]

Autolog 3000 Specification. http://www.peekel.de/download/Autolog3000.pdf [Accessed on 09.07.2020]

DIN 1342-2. Viscosity - Part 2: Newtonian liquids

DIN 51562. Viscometry - Measurement of kinematic viscosity by means of the Ubbelohde viscometer.

DIN 51605. Fuels for vegetable oil compatible combustion engines - Fuel from rapeseed oil - Requirements and test methods

Esteban, B., Riba, J-R., Baquero, G., Rius, A., Puig, R., (2012), Temperature dependence of density and viscosity of vegetable oils – Biomass and Bioenergy Vol. 42, 164-171.

Fernando, S.D. and Hanna, M. (2006), Lubricity characteristics of selected vegetable oils, animal fats and their derivatives. Applied Engineering Agriculture Vol. 23(1), 5-11.

Labview Version 2015 Download. https://www.ni.com/de-de/support/downloads/software-products/download.labview.html#306324 [Accessed on 09.07.2020]

Product Information Molykote PG-75. https://www.ulbrich-group.com/chemical-technical-products/TDS_MOLYKOTE_PG_75_eng.pdf [Accessed on 09.07.2020]