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DEVELOPMENT OF SIMPLE EXPERIMENTAL METHODS FOR DETERMINING THE COEFFICIENT OF SLIDING AND ROLLING FRICTION

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Abstract: In the article slip and rolling friction coefficients determination styles work developed. Steel basis on the surface cylindrical copper, steel, cast iron, aluminum bodies in sliding static and kinetic friction features identified and affected doer to power dependence graphics received. Also simple experience device through rolling friction coefficient to determine theoretical and experiential ways shown.

Keywords: Friction, sliding, rolling, static, kinetic, equilibrium, motion, weight, normal pressure, steel, copper, aluminum, cast iron, steel, friction angle, steel spherical, concave beam, period of oscillations , initial speed , final time.

Introduction. The phenomenon of friction occurs on the touching surfaces of different bodies in contact. Friction, in turn, has a static and dynamic character. Friction that opposes the movement of an object on the surface of another object and keeps it in equilibrium is called static friction or friction at rest. There are also types of kinetic sliding friction and rolling friction that occur on the contact surfaces of bodies in contact and moving relative to each other. The force of friction is represented by the results of the natural electromagnetic effect between the molecules and atoms of the adjacent layers interacting [1-3].

Determination method: coefficient of sliding friction. A let the body (for example, a prismatic rod) lie on a fixed base (board) (Fig. 1). We A slowly Fapply an external force to the body and continuously increase it. Initially A body in its own equilibrium situation save stands. In this case to the body effect doer external F the force A is balanced by the tangential friction force in the opposite direction to the external force caused by friction on the contact surface of the body F_{ish} and the base. This type friction power mutually in contact has been but, one to one relatively not moving in bodies surface will come and this friction called static friction [7]. If external strength maximum friction power $F_{ish}$is smaller than the value, the objects are one to one relatively does not move. Because static friction power external strength effect compensates.

External strength of the module effect when, the maximum to value when achieved (i.e that's it in case static friction of strength value to the maximum achieves) body A basis on the surface slip to move starts. This is friction power your body movement influence during is enough on the slide friction the modulus of strength is relative movement to the speed depends will be [9].

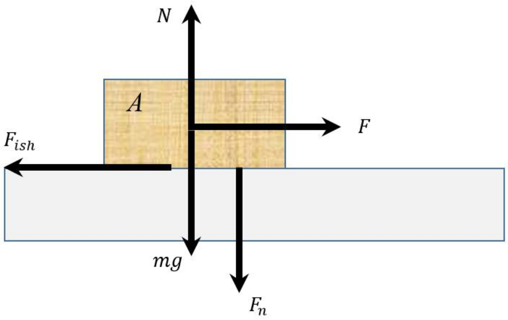


Figure 1. Acting force on sliding friction.

Dry friction strength determiner empiric formula French physicists Amonton Guillaume (Guillaume Amontons; 1663-1705) and Pendant By Charles (Coulomb Charles Augustin; 1736-1806). offer done. To the law according to maximum static friction module of force contact to the surface depends without being, friction normal pressure on the surface to the power right proportional being as follows is expressed [1-4]:

$$F_{ish-max} = \mu_0 F_N \tag{1}$$

Where μ_0 −static friction coefficient contact of surfaces properties depends will be below contactor in table 1 given materials for friction coefficient given.

Table 1

Material 1	*Steel*	*Steel*	*Steel*	*Metal*	*Rubber*	*Wood*
Material 2	*Ice*	*Steel*	*Plastic*	*Wood*	*Asphalt*	*Wood*
μ_0	0,015	0,15	0,3	0,5	0,55	0,65

Analog expression in the manner (1) as follows to write can:

$$F_{ish} = \mu F_n. \tag{2}$$

Where, μ −the sliding friction coefficient.

Newton's the third to the law according to pressure the value of the modulus of force is the normal reaction power to the value of equal to that's why for friction strength determination expression the following way our writing possible (Fig. 1):

$$F_{ish} = \mu N. \tag{3}$$

Experience of the object description. Experimental studies were carried out on the TM-21A device (Fig. 2). Device friction coefficient and friction angle values determination enable will give. Device base 1, board known angle deviation enable giver hinge 2, board 3, protractor 4, cylindrical shaped load 5 and dynamometer 6.

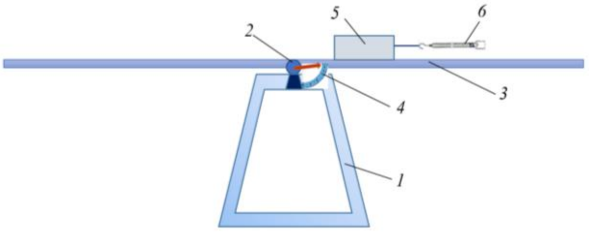


Figure 2. Experimental device.

a- Scheme of the experimental device, b- experiment process.

Slippery bodies as steel, cast iron, brass, aluminum materials was selected (Figure 3).

a *b* *d* *e*

Figure 3. Slippery materials: a- copper , b- cast iron , d- steel , e- aluminum

Friction coefficient determination:

First in line $F_N = mg$ according to the expression: slippery of bodies weight forces determined:

Copper of the cylinder weight: $F_N = 1{,}370kg \cdot 9{,}81\frac{N}{kg} = 13{,}4397N$;

Cast iron of the cylinder weight: $F_N = 1{,}180kg \cdot 9{,}81\frac{N}{kg} = 11{,}5758N$;

Steel of the cylinder weight: $F_N = 1{,}245kg \cdot 9{,}81\frac{N}{kg} = 12{,}21345\ N$;

Aluminum of the cylinder weight: $F_N = 0{,}480kg \cdot 9{,}81\frac{N}{kg} = 4{,}7088N$.

Basis blackboard on top of it slippery bodies one go away putting, slippery of the body weight center past to the plain horizontal way electron dynamometer through strength effect (Fig. 4).

Figure 4. Process of determining static and kinetic friction.

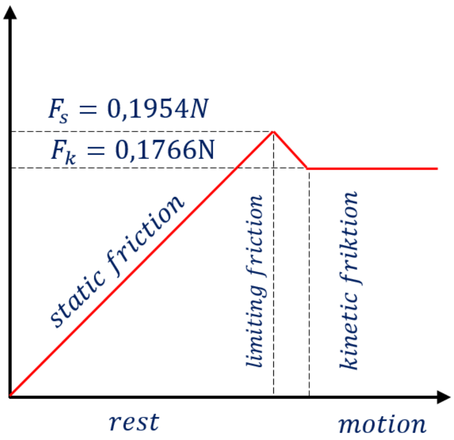
The body out of balance issuer maximum strength of any value one condition for was determined. Try this experiment 3 times Repeatedly average. The value is included in Table 2. The following expression through friction coefficient determined [7-10]:

$$\mu_0 = \frac{F_{ish-max}}{F_N} \qquad (4)$$

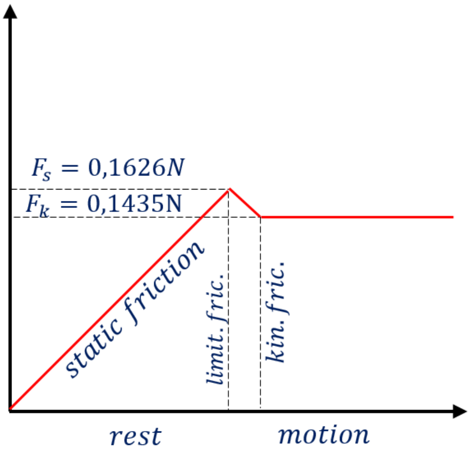
Static and kinetic friction values the body instigator to power dependence the graph is presented in Figure 4.

Table 2

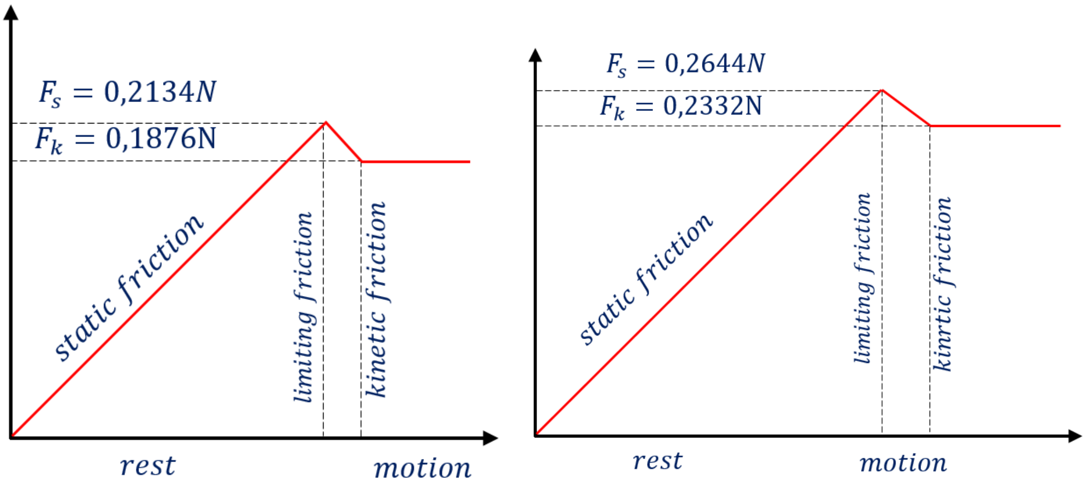
Board material	Slippery the body material	F_N, N	$F_{ish-max}$, N	Friction coefficient , μ_s	Motion (kinetic) friction μ_k
Steel	Copper	13,4397	2,6269	0,1954	0.1766
Steel	Cast iron	11,5758	1.8823	0.1626	0.1435
Steel	Steel	12,21345	2.6064	0.2134	0.1876
Steel	Aluminum	4,7088	1.2403	0.2644	0.2332



Steel – copper



Steel – cast iron



Steel – steel

Steel – aluminum

Figure 5. Graph of force dependence of static and kinetic friction coefficient values.

b. Friction coefficient Let's go balance angle through determination:

Slippery of the body weight strength let's find out . Basis blackboard on top of it slippery the body put the board horizontal to the plain relatively slowly slowly with twist we will go. In this the body with blackboard between friction of strength at the expense of the body one lifetime in equilibrium that there is let's see. Can of the board deviation angle which one to value when you reach, of the body out of balance that it came out to determine can. This experience each one case for 3 times repetition and average value get to the goal according to is considered. The body out of balance issuer maximum angle to the value of suitable respectively the circuit in Figure 6 below seeing we go out. Body horizontal basically known α angle when turned, to the base of the body weight mg, own weight at the expense of surface coming, the body to action to bring attempter strength $mgsin\alpha$ and the frictional force in the opposite direction to the body's motion $F_{ish}$and the normal reaction force that keep the body in equilibrium N effect reaches [1-5].

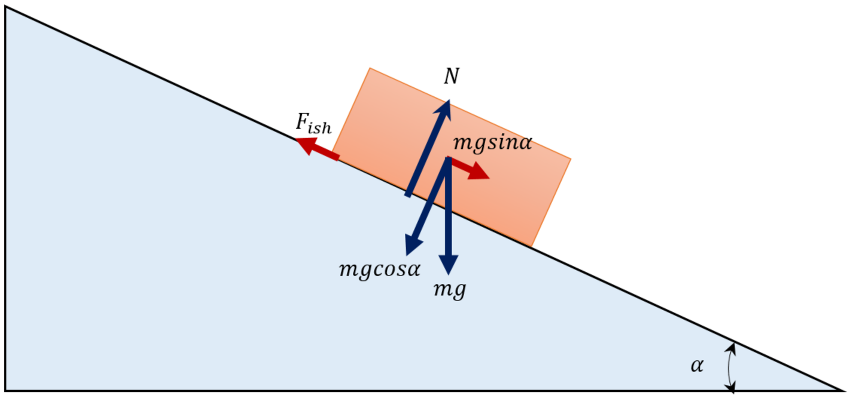


Figure 6. Balance angle through friction coefficient determination scheme.

In this case, the value of friction force the following expression to be determined:

$$F_{ish} = mgsin\alpha, \tag{5}$$

Also to the body effect normal reaction force value:

$$N = mgcos\alpha, \tag{6}$$

In that case friction coefficient:

$$\mu = \frac{F_{ish}}{N} = tg\alpha. \tag{7}$$

The body out of balance issuer angle value each one case for determined and included in table 3.

Table 3.

Board	Slippery the body material	The body out of balance issuer maximum angle, α,°	Friction coefficient , μ = tgα
Steel	Copper	13°15′	0.2354
Steel	Cast iron	13°30′	0.2400
Steel	Steel	16°30′	0.2962
Steel	Aluminum	18°30′	0.3443

Determination of rolling friction. In Figure 7 below, a cart with mass m is moving with speed v in a horizontal plane. The normal force acting on the cart from the plane is equal to:

$$F_N = mg \tag{8 }$$

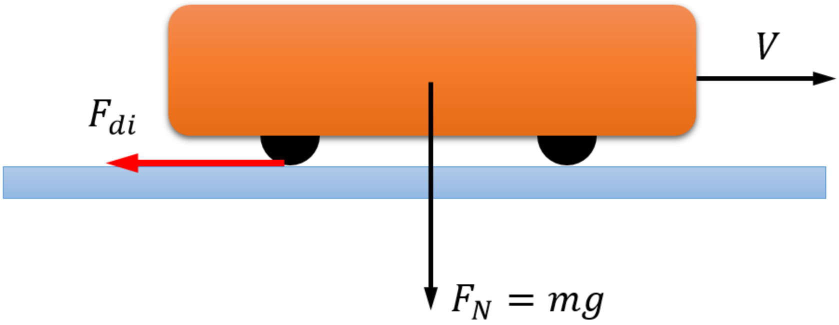


Figure 7. Scheme of rolling friction.

Known from the theory of friction that the frictional force on the wheels of the cart F_{di} is in the opposite direction to the movement. Determination of rolling resistance or rolling friction coefficient is carried out by the following expression [3]:

$$C_d = \frac{F_{di}}{F_N}, \tag{9 }$$

The force of rolling friction based on Newton's second law $F_{di} = ma$, then the coefficient of rolling friction takes the following form:

$$C_d = \frac{ma}{mg} = \frac{|a|}{g}, \tag{10 }$$

where a −the deceleration of the cart is the acceleration and is parallel to the cart.

Rolling friction causes the stroller to slow down in the opposite direction of motion. The rolling resistance will be of very small value. For example: rolling resistance between steel wheels moving on a steel rail $10^{-3}$is smaller [1-3]. Based on the above-mentioned points, it can be noted that the value of the friction force in rolling is much smaller than in sliding.

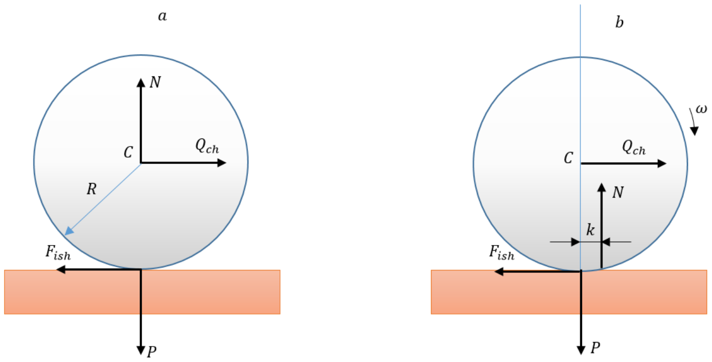


Figure 8. Description of the forces that occur during rolling.

At the limit state, the wheel is subjected to two pairs of forces, the first of which is Q_{ch} and F_{ish} is its moment $M = Q_{ch} \cdot R$ (here R −the radius of the rolling object), and the second is the balancing P and N pair of forces whose moment is $N \cdot k$ is equal to the turning and resisting moments are mutually equal in the limit state, that is, $Q_{ch} \cdot R = N \cdot k$ or

$$Q_{ch} = \frac{k \cdot N}{R}, \qquad (11\ )$$

where, Q_{ch} −the boundary friction force, k − rolling friction coefficient, N −normal pressure.

Sliding friction coefficient μ and rolling friction coefficient k are obtained from special tables. Table 4 below shows the values of the rolling friction coefficient for various materials [10].

Table 4.

Roll up condition	**Coefficient of rolling friction, *k***
Steel wheel on steel rail	0,05
Wooden box on wood	0,05 − 0.08
Steel wheel on wood	0,15 − 0,25
Rubber balloon on asphalt surface	0,02
Wooden wheel on steel	0,03 − 0,04
A steel ball on a steel surface	0,0005 − 0,0010

There are a number of methods for determining the rolling friction coefficient k. This simple experiment method can be performed by students and the results are very reliable. It is known that various factors can affect the friction force in rolling, including viscosity, deformation, elastic, friction, etc. [1]. In the experiment, we determine Q_{ch} the value of the rolling friction force k using the coefficient of rolling friction and the normal force being proportional to N:

$$Q_{ch} = kN \tag{12 }$$

(12), the only dissipative force (kinetic and potential energy) that causes a change in mechanical energy in this case is the rolling friction force. Diameter as a rolling body 3,00 sm and $m = 110\, g$a steel ball with mass and a steel concave surface corridor were used (Fig. 9).

Figure 9. A device for determining the coefficient of rolling friction.

A ball is released from equilibrium along a concave surface at a fixed distance from the center. The movement of the ball on the track along the concave surface was detected with the help of a camera that determined the time and the position of the maximum deviation. From the results of the experiment, it is known that increasing the radius of curvature of the corridor $s$leads to an increase in the path of the ball and the time to return to equilibrium Δt. Figure 10 shows graphs of the position and velocity of the ball versus time for a $m = 225\, g$ steel ball with a diameter of 3.90 cm and a mass of 0.57 meters and a wooden rod with a radius of curvature of 0.57 meters and a limit of displacement from the equilibrium position of 0. The results of the research conducted in parameters of 0.15 meters are presented. Since the curvature of the concave surface is very small, the movement of the ball $N = mg$ is assumed to be uniform (equal) with a constant normal force. Even the largest displacement of the sphere from the equilibrium position in the concave path with the 0,15 m radius of curvature 0,57 m varies only by 3% from the value of the normal force $-mg$. We can see this by the following expression [1-4]:

$$N = mgcos\left(\frac{0{,}15}{0{,}57}\right) = 0.97mg.$$

If a ball moving on a concave surface rolls without slipping, K the change in kinetic energy is considered as a single force, the force of rolling friction and the forces of gravity. It is possible to determine the work performed by the metal sphere at the initial and lower point of the concave surface until the final equilibrium state (after several oscillations) from the law of change of kinetic energy. It can be noted that the change in the kinetic energy of the ball is equal to the work done by the rolling friction force. The kinetic energy of a steel ball rolling on a flat surface K can be considered to be equal to the sum of the kinetic energy of the ball moving forward and rolling K_d(relative to the center of mass). K_iThen we determine the kinetic energy of the steel ball with the following expression:

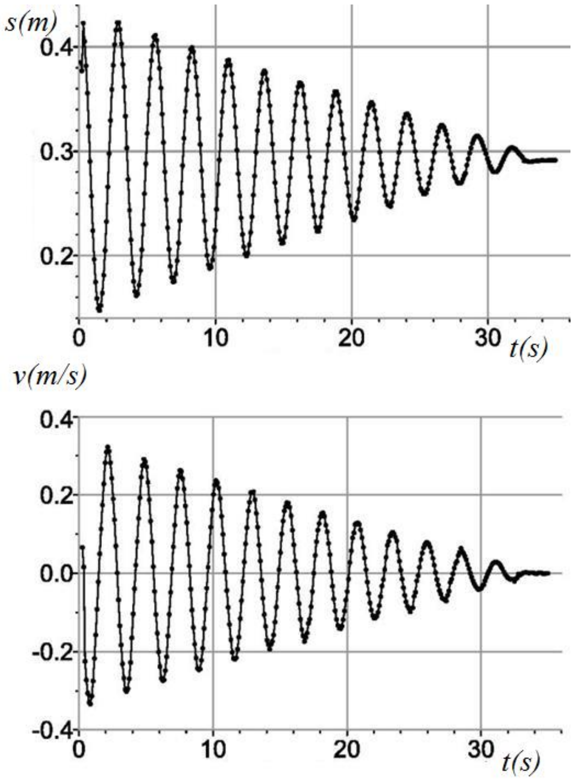


Figure 4.3. A graph representing the change in position and velocity of the ball over time. Diameter as a rolling ball 3,90 sm and m = 225 g, the radius of curvature determined by the dimensions of a steel ball and a length made of wood is 0.57 meters, and the limit of displacement from the equilibrium position is 0.0.15 meters for the case [1].

$$K = K_i + K_d = \frac{1}{2}mv^2 + \frac{1}{5}mv^2 = \frac{7}{10}mv^2 \qquad (13)$$

where v –the speed of the center of mass of the steel ball is m/s.

Based on the above expressions, the work performed by the rolling friction force of the metal ball W is determined by the following expression:

$$\mathrm{W = kmgs.} \qquad (14)$$

where is s −the total distance traveled by the metal ball, m.

If we take into account that the work done is equivalent to the fully spent kinetic energy, the expression can be written as follows:

$$\frac{7}{10}mv^2=\text{kmgs}. \tag{15 }$$

(15), we can determine the rolling friction coefficient:

$$k=\frac{7mv^2}{10\,mgs}. \tag{16 }$$

The reduction in the expression and the speed of the metal ball $t=1\,s$ at the beginning v_b and the speed at which it reaches equilibrium v_o (this t_b −means the time it takes for the metal ball to reach equilibrium), that is, $v^2=v_b^2-v_0^2$ the coefficient of friction in rolling can be determined as follows:

$$k=\frac{7(v_b^2-v_0^2)}{10\,gs}. \tag{17}$$

The total distance traveled by the ball s −can also be calculated from high-resolution video footage, and s we can also determine, as the sum of swing distances, using the following expression:

$$s=\left(\frac{2\,(A_b-A_0)\Delta t}{T}\right), \tag{18 }$$

where, A_b, A_0respectively, the amplitude of the initial and final steel ball relative to the equilibrium position, T −the period of oscillation, $\Delta t=t_b-t_0$.

Then the expression for determining the rolling friction coefficient is as follows:

$$k=\frac{7}{20}\frac{T(v_b^2-v_0^2)}{g(A_b-A_0)\Delta t} \tag{19 }$$

Continuing our research, let's conduct an experiment on a steel ball moving on a corridor with a radius of curvature of 1.35 meters shown in Figure 9. In this:

the diameter of the steel ball $d_{sh}=3{,}00sm$;
the mass of the steel ball $m_{sh}=110\ g$;
the radius of curvature of the steel beam $r=1{,}35m$;
$A_b=0{,}35m$ − the amplitude of the initial positsion;
initial time of ball movement $t_b=1sek$;
the time from movement to balancing $t_o=1sek$;
speed of the ball in the initial 1 second $v_b=0{,}6m/s$;
velocity of the sphere in equilibrium $v_0=0$;
period of movement of the ball $T=3{,}8\ sek$.

If we determine the rolling friction coefficient according to the expression (19):

$$k=\frac{7}{20}\frac{T(v_b^2-v_0^2)}{g(A_b-A_0)\Delta t}=\frac{7}{20}\frac{3{,}8sek((0{,}6m/sek)^2-0)}{9{,}81\frac{m}{sek^2}(0{,}35m-0)35{,}85\ sek}=3.89\cdot10^{-3}$$

Conclusion. Based on the results of the conducted research, it can be said that the friction that occurs as a result of the mutual contact of different materials has a unique complex character. Relatively large differences between the values of the coefficient of friction in sliding and rolling determined in the research results and the values of the existing research results are explained by the complex nature of the friction process.

Static and kinetic friction coefficients of sliding objects on a steel base: steel, cast iron, brass, aluminum cylinders were determined by a simple experimental method. Coefficient of static friction in a pair of copper cylinders sliding on a steel base $\mu_s = 0{,}1954$, coefficient of kinetic friction, $\mu_k = 0{,}1766$ coefficient of static friction $\mu_s = 0{,}1626$ in a pair of steel-cast iron, coefficient of kinetic friction , $\mu_k = 0{,}1435$coefficient of static friction $\mu_s = 0{,}2134$in a pair of steel-steel, coefficient of kinetic friction $\mu_k = 0{,}1876$, po lat was the coefficient of static friction $\mu_s = 0{,}2644$ and the coefficient of kinetic friction in the aluminum pair $\mu_k = 0{,}2332$.The fact that these values differ from previous studies requires that external factors be fully taken into account when studying the nature of friction. Implemented experiential research to the results according to obtained (Fig. 5) bond graphics static and kinetic friction coefficient values between relationship complete imagination reach enable will give.

Friction coefficient value define again one simple method, sliding of the body balance angle determination the experience was also conducted. Research during basically slippery of the body in equilibrium issuer angles identified there is to expressions suitable without friction coefficients was determined. In this: steel-copper in pairs $\alpha = 13°15'$, $\mu = 0{,}2354$, steel and cast iron in pairs $\alpha = 13°30'$, $\mu = 0{,}2400$, steel-steel in pairs $\alpha = 16°30'$, $\mu = 0{,}2962$, steel-aluminum in pairs $\alpha = 18°30'$, $\mu = 0{,}3443$ edit the values.

Rolling friction coefficient to determine to himself characteristic please received without rolling friction coefficient determiner simple experience device work released and the diameter $d_{sh} = 3{,}00sm$ of the steel ball, the mass $m_{sh} = 110\ g$, is the radius of curvature of the steel bar$r = 1{,}35m$ in case rolling friction coefficient was determined. Experience as a result according to rolling friction of the coefficient value $k = 3.89 \cdot 10^{-3}$organized.

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