XV. *Experiments on the friction and abrasion of the surfaces of solids.* *By* George Rennie, *Esq. F.R.S.*

Read June 12, 1828.

THE paper now offered to the consideration of the Royal Society, comprises the results of part of a series of experiments undertaken in the year 1825, with a view to determine the measure of the retardations of bodies in motion, when affected by the attrition of their surfaces, and by mediums of different densities.

From the attention that has hitherto been paid to this important branch of mechanical science, and from the many elaborate dissertations and experiments that have appeared at different periods, it would naturally be concluded, that the subject had been so fully elucidated, as to admit of little if any further investigation: but the diversity of opinions still prevalent among philosophers, and the difficulty of reducing to a satisfactory state the doctrines already advanced, incline me to the opinion that the subject is as yet but imperfectly understood. This may be attributed in a great degree to the very defective state of our knowledge of the properties of materials, and the difficulty or rather impossibility of subjecting them to geometrical mensuration. The science of mechanics considers forces as reduced to the simple questions of mathematical analysis, without regard to the properties of matter or the phænomena incident thereto: but in rendering forces sensible, we are necessarily compelled to make use of agents, or intermediate bodies termed machines, the employment of which in transmitting motion, in modifying its action, or in restoring the equilibrium between forces of different intensities, constitutes the object of every mechanical operation. The solution of this question therefore involves the conditions of equilibrium, both of simple and compound machines; the transmission of motion under different circumstances; the construction and combination of the different parts of machines, and the properties of the materials of which these parts are composed.

On a former occasion an attempt was made to develope some of the properties of solid bodies in resisting the action of a disruptive force*, the measure of which was represented by the sum and qualities of the particles displaced. The connection may be traced in the present inquiry, which relates principally to the resistance arising from the displacement, or rupture of the superficial asperities of bodies in motion when brought into contact by extreme pressure, and is analogous to the cohesive state of a body acted upon by opposite but contrary forces. But the cases investigated by experimentalists have seldom been carried to the extent necessary to produce a disrupture of the prominencies, being generally confined to the definition of friction as designated by writers on mechanics, to be the force expended in raising continually the surface of pressure by an oblique action; the surfaces being represented by a series of inclined planes acting against each other in alternate succession. The measure of friction therefore being supposed to depend upon the angles of the prominencies and the elementary structure of the bodies, the effect of polishing could only be to diminish those prominencies without altering their curvature or inflections. The expense of force therefore ought still to remain the same in both cases†. In this hypothesis it is reasonable to concur, experiment proving, that the amount of friction bears immediate reference to the elementary structure of bodies; and although the doctrine of inclined planes admits of a ready comprehension of the causes of this kind of resistance under certain circumstances, a very slight investigation of the nature of the bodies themselves will exhibit their asperities under every possible configuration. The amount of resistance will depend upon the degree of pressure, the approximation or rather the engagement of the asperities and concavities, and the nature of the surfaces of which fibrous, soft, or hard bodies are composed. To surmount, bend, or detach these asperities under the circumstances of pressure, area, and velocity, demands a proportionable exertion of force; and it is by the determination of this force under all cases, that we can alone arrive at an estimation of the performance of machines.

The nature of friction has excited the attention of most of the writers on mechanics, from the period of the first two dissertations of Amontons in the

* Experiments on the Strength of Materials:—Philosophical Transactions 1817.

† Leslie's Experimental Philosophy.

year 1699, down to the more elaborate researches of COULOMB and VINCE in 1779 and 1784. AMONTONS was the first that attempted to develope and reduce theory to calculation. He affirmed that friction was not augmented by an increase of surface, but only by an increase of pressure*; and in a subsequent paper, illustrated by some experiments on wood and metals pressed by springs of known intensity, he drew similar conclusions, with the addition that friction was $\frac{1}{3}$rd of the pressure, and that the amount was the same both with wood and metals when unguents were interposed. He likewise concluded, that friction increased or diminished with the velocity, and varied in the ratio of the weight and pressure of the rubbing parts, and the times and velocities of their motions. These hypotheses were adopted more or less by most of the philosophers after AMONTONS, but particularly by DE LA HIRE†, who satisfied himself by several experiments of the truth of AMONTONS' conclusions; but they were questioned by LAMBERT, although without the test of experiment. PARENT suggested an investigation of the subject in his proposition of the Spheres, and by determining the angle of equilibrium, at which a body resting on an inclined plane commenced sliding. And the celebrated EULER, in a very elaborate paper‡, conceived it to depend upon the greater or less approximation of the asperities of the surfaces brought into contact by pressure, the resistance to which he allows to be $\frac{1}{3}$rd of the pressure; the same as AMONTONS. Of the effect of velocities he was however uncertain; but observed that when a body begins to descend an inclined plane, the friction of the body will be to its weight or pressure upon the plane, as the sine of the plane's elevation to its cosine, &c. But when the body is in motion, the friction is diminished one half. MUSCHENBROEK and others maintained that friction increased with the surface; and BOSSUT distinguished it into two kinds; the first being generated by the gliding, and the second by the rolling of the surface of a body over another: and remarked, that it was affected by time, but that it neither followed the ratio of the pressure nor the mass. BRISSON§ attempted to construct a table of coefficients, to denote the value of the friction of different substances; but they are inapplicable to practical purposes, for want of proper experiments. DESAGULIERS considered the nature of friction with a good deal of attention,

* Sur la Force des Hommes et des Chevaux, et de la Resistance causé dans les Machines.

† Mémoires de l'Academie des Sciences. ‡ Ibid.

§ BRISSON, Traité de Physique.

but principally with reference to the rigidity of cords. He however quotes the experiments of Camus as best calculated to illustrate the subject; nevertheless they were made on too small a scale to derive any satisfactory conclusions. Schober and Meister coincided with Muschenbroek in the opinion, that the spaces were as the squares of the times in the case of a body uniformly accelerated. The opinions of many other eminent philosophers, such as Leibnitz, Varignon, Leupold, Bulfinger, Daniel Bernoulli, Ferguson, Rondelet, Gregory, Leslie, Young, Olivier*, &c. might be quoted. But it is to Coulomb principally that we are indebted for the knowledge we possess of this kind of resistance.

In the year 1779 the Academy of Sciences at Paris, being desirous of rendering the laws of friction, and the effects resulting from the rigidity of cords applicable to machines,—Coulomb undertook in the arsenal at Rochfort a very extensive series of experiments, which he afterwards published in 1781 under the title of "Théorié des Machines simples, en ayant égard au Frottement de leurs Parties, et à la Roideur des Cordages†." The memoir is divided into two parts. The first treats of the friction of surfaces gliding over each other, and the second enters into an examination of the rigidity of cords, and the friction of the rotary movements of axles. Coulomb commences his work by examining the friction of plane surfaces gliding over each other, distinguishing it into two kinds; the first resulting from time, and the second from velocity. The first may depend on four different causes, viz.

1st. The nature of the bodies in contact.

2nd. The extent of surface.

3rd. The pressure on the surface.

4th. The time the surfaces have been in contact. And he even adds a

5th. The state of the atmosphere; which he however thinks may have little influence.

The case of bodies gliding over each other with a certain velocity he considered to be referable to the first three causes, besides the velocity of the planes in contact.

With regard to the physical cause of friction, he coincides with the opinions of Amontons and others, that it arises from the entangling of the asperities,

* Sur les diverses Espèces de Frottements, &c. (not published.)

† Mémoires des Sçavans Etrangers, tome 163 & 333.

which can only be disengaged by bending or breaking. These experiments led to some important results, viz.

1st. That the friction of wood on wood without unguents was in proportion to the pressure which attained its maximum in a few minutes after repose.

2nd. That the effects of velocities were similar; but the intensities were much less to keep the body in motion, than to detach it from a state of rest, oftentimes in the ratio of 22 : 95.

3rd. That in the case of the metals the results were likewise similar; but the intensity was the same whether to disturb or maintain the motion of the body.

4th. That with heterogeneous surfaces, such as those of woods and metals gliding over each, the intensity did not attain its limit sometimes for days.

In general, however, with woods and metals without unguents, velocities were found to have very little influence in augmenting friction, except under peculiar circumstances.

The treatise of COULOMB is illustrated by a great variety of interesting experiments, and forms the most valuable work we possess on the subject.

In the year 1784, Dr. VINCE endeavoured by some very ingenious experiments to determine the law of retardation together with the quantity, and the effect of surface on friction. The results were, that the friction of hard bodies in motion was an uniformly retarding force, but not so with cloth and woollen, which were found in all cases to produce an increase of retardation with an increase of velocity.

That the quantity of friction amounted to about $\frac{1}{4}$th of the pressure, and that it increased in a less ratio than the quantity of matter or weight of the body.

That when the surfaces varied from 1.61 : 1 to 10.06 : 1, the smallest surface gave the least friction: and finally, that friction was greatly influenced by cohesion.

Dr. VINCE's conclusions regarding the laws of retardation were partly confirmed by the late ingenious Mr. SOUTHERN of Soho, who in a letter to Dr. VINCE in 1801, communicated the results of several experiments on the surfaces of the spindles of grindstones moving with great velocities; when it was found that with the rubbing surfaces moving at the rate of 4 feet per second over a length of surface of 1000 feet, the resistance arising from the friction of 3700lbs. of matter, only amounted to $\frac{1}{40}$th of the weight.

In the year 1786 and subsequently, the late Mr. RENNIE made several experiments on the friction and resistance of heavy machinery. The results varied under different circumstances; but it appeared that an augmentation of resistance took place in proportion to the quantity of machinery put into action. In one instance in the ratio of 1 to 5, when it absorbed from one-fifth to one-tenth of the power expended.

This anomaly, as compared with the ratio of surfaces in the present experiments, can only be accounted for, from the irregularity of the movements and the difficulty of producing simultaneous actions in complicated machinery; the more especially as the results were affected by contingencies which could not be properly estimated; some of the elements on which the deduction is founded not being stated. The resistance was likewise increased by reversing the direction of motion. The velocities being very moderate, and hardly exceeding 120 feet a minute, appeared to have had no influence: but the experiments related principally to the resistances produced by different kinds of machinery. The experiments of M. Boistard* on the gliding of stones with a view to develope the equilibrium of arches, led him to conclude that the relation of the friction to the pressure was constant; that asperity of surface did not alter its value, which generally amounted to $\frac{4}{5}$ths of the pressure.

From similar experiments M. Rondelet concluded†,

1st. That the rougher the surface of stones, the greater the power required to move them.

2nd. That the greater the insistent weight, the greater the resistance: but as the inequalities are apt to be broken, the maximum force required to over come the friction ought to be equal to produce that effect, whatever be the weight of the stone.

3rd. That this force ought rather to be in the ratio of the hardness of the stone than of its weight.

4th. The amount of friction varied from one-half to one-third of the insistent weight.

5th. The angle of equilibrium of similar stones was about 30 degrees. And

6th. Finally, extent of surface did not alter its value.

The experiments of Morisot on the grinding and polishing of stones, and of Maniel and Pasley on the pressure and equilibrium of earths, present

* Recueil d'Experiences et d'Observations, &c. sur le Pont de Nemours.

† L'Art de Batir. Tome iii. 1808.

some interesting results; but it is only recently that our knowledge of the subject has been materially enlarged.

The agitation of the canal and rail-road question in the years 1824 and 1825, and the invention or rather revival of a mode of applying steam in lieu of animals to carriages on rail-roads, led to the most extravagant conclusions: and although the doctrines of COULOMB and VINCE, relative to the equality of resistances under different velocities, have been still further confirmed by the experiments of many able persons in this country, such as CHAPMAN, GRIMSHAW, WOOD, TREDGOLD, PALMER, ROBERTS, and others, and much valuable information elicited;—our progress in the science has been but slow and unsatisfactory. Sensible of these defects, and being unable to profit by the valuable treatises subsequently published, it occurred to me that a series of experiments founded on the omissions of former writers would be extremely desirable.

The present series of experiments relates to the friction of attrition. This branch of the science comprehends the resistance occasioned by solid bodies,—such as ice, cloth, paper, leather, wood, stones, metals, &c. gliding over each other simply, or by the intervention of semi-fluids or unguents, such as oil, tallow, &c.

The object has likewise been to determine the powers to resist abrasion under the circumstances of surface, pressure, and velocity. Examples have been sought,

1st. From ice, by the resistance of its surface to sledges, skates, &c.

2nd. From cloth, by its remarkable properties of resistance in opposition to the law observed by solids.

3rd. From leather, by its great utility in the pistons of pumps, &c.

4th. From wood, in its application to pile driving, carpentry, launching of ships, &c.

5th. From stones, as relating to the equilibrium of arches and buildings. And

6th. From metals, from their universal application to machinery; but more particularly to wheel carriages and rail and other roads, on which a great many experiments have been made.

Experiments on a great scale, however, frequently involve so many contradictions, from the difficulty of obtaining the necessary elements, that I have deemed it preferable to offer the present series, as comprehending in a greater degree most of the cases in question, and affording a more systematic view of the nature of the investigation.

The apparatus employed in performing the experiments on the friction of attrition, Plate IV, consists simply of a strong table accurately made and adjusted, and provided with a platform capable of being elevated to any angle within thirty degrees, as shown by the graduated arc. The substances tried were placed on the platform and in the sliding block above, to which the scale and weights for bringing the substances into closer contact were suspended: a cord going over a pulley was attached to the sliding block, which received its motion from weights put into the moving scale. The different phænomena were then accurately recorded, as appears by the accompanying Tables, and the conclusions derived from them.

Table I.

Experiments on the Friction of 3 square inches surface with Cloth.

Black Single Kerseymere. No. 1.

Weight on surface.	Weight required to move it.		Proportion.
lbs.	lbs.	oz.	
1	1	6	
2	2	4	
5	4	2	1 21
10	6	4	1 60
20	9	13	2 03
28	13	2	2 13
56	20	11	2 70

Superfine Blue. No. 2.

Weight on surface.	Weight required to move it.		Proportion.
lbs.	lbs.	oz.	
1	1	3	
2	2	12	
5	5	3	
10	8	4	1 21
20	12	11	1 57
28	15	5	1 82
56	22	11	2 47

Drab Milled Kerseymere. No. 3.

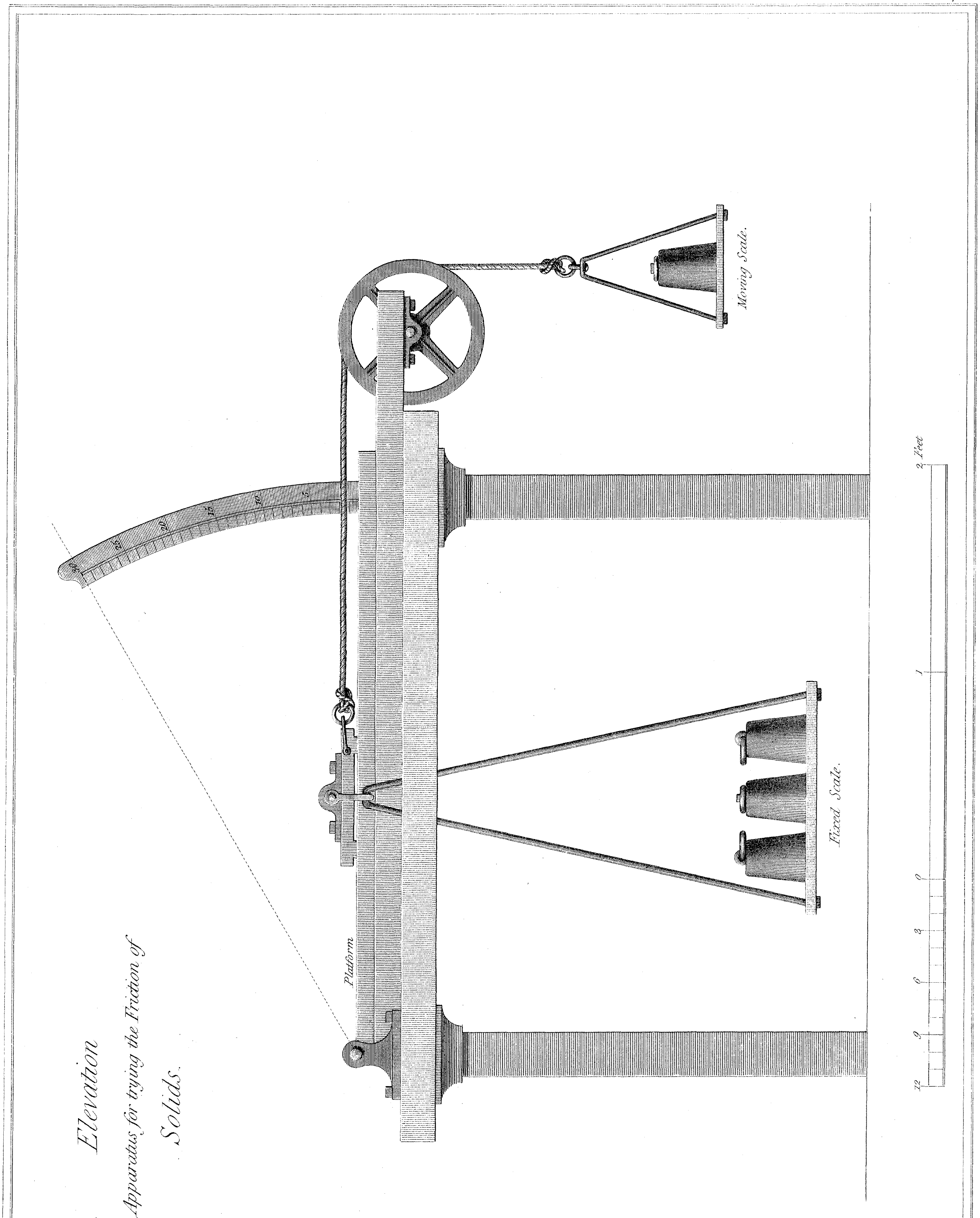
Weight on surface.	Weight required to move it.			Proportion.
lbs.		lbs.	oz.	
1		1	11	
2		2	11	
5		5	3	
10	took 2½ lbs. in addition to start it	7	13	1 28
10	after remaing 12 hrs. it took to start it	12	10	
20		12	11	1 57
28		16	7	1 70
56		25	3	2 22

Drab Kersey Hunter. No. 4.

Weight on surface.	Weight required to move it.		Proportion.
lbs.	lbs.	oz.	
1	1	5	
2	1	15	1 03
5	3	8	1 43
10	5	4	1 90
20	8	11	2 30
28	10	0	2 80
56	19	3	2 92

Strong Drab. No. 5.

Weight on surface.	Weight required to move it.		Proportion.
lbs.	lbs.	oz.	
1	0	15	1 06
2	1	8	1 33
5	3	2	1 60
10	4	11	2 13
20	7	11	2 60
28	9	12	2 87
56	17	14	3 13



Elevation of the Apparatus for trying the Friction of Solids.

Jas Basire sc.

Remarks.

1. That with fibrous substances, such as cloth, friction diminishes with an increase of weight.
2. That friction is greater (cæteris paribus) with fine cloths than with coarse cloths.
3. That friction is greatly increased by time.
4. That friction varies from one-third to an amount greater than the total weight.

Table II. Experiments on the Velocities with Drab Milled Kerseymere, No. 3.

Weight on surface.	Weight required to move it.	Total space passed over.	Time in seconds.	Remarks.
Of 9 square inches surface.				
lbs.	lbs. oz.	inches.		
1	1 8	24	45	From 1lb. to 2lbs. the adhesion is greater than the weight on surface.
			32	
			30	
			22	
			23	Velocities very irregular.
1	1 5		24	
			25	
			40	
			37	
2	2 5		31	Velocities very irregular.
		half way in 17 sec. the whole in	26	
			17 27	* Denote the experiments that approximate the nearest to an uniform velocity.
2	2 5		21 30*	
			33 53	
			17 30*	Results very irregular, owing perhaps to the fibres of the cloth having been previously compressed.
5	4 3		29 45	
10	6 7	mean of 3 trials	45 63	
20	9 7		30 50	
Of 18 square inches surface.				
lbs.	lbs. oz.	inches.	1st half. 2nd half.	Increase of surface shows an increase of resistance with equal weights of 20lbs.
20	13 6	mean of 3 trials 21	22 33	
20	after remaing 14 hrs. it took to start it 23 3			Time nearly doubles the resistance.
Of 27 square inches surface.				
lbs.	lbs. oz.	inches.	1st half. 2nd half.	Three times the surface nearly three times the resistance.—Velocities irregular. Vide Vince's Experiments.
1	2 8	mean of 3 trials 18	4 14	
2	3 10		30 73	
5	6 7		25 60	
10	10 2		28 55	Nearly uniform.

1. From the foregoing experiments it appears that velocities observe no particular law, except in three instances, where the last halves of the space passed over approximate to the first halves.
2. That increase of surface very much increases the resistance.

Table III. On the Friction with Cloth at different angles of elevation.

Weight on surface.	Moved at degrees.	Space passed over.	Time in seconds.	Proportion.	Weight on surface.	Moved at degrees.	Space passed over.	Time in seconds.	Proportion.
Of 3 square inches.					Of 27 square inches.				
lbs.	°	inches.			lbs. oz.	°	inches.		
10	37.00	24	55	1.327	13 8	45.00	18	32	1.000
20	28.20		55	1.855	20 0	40.30		42	1.171
28	26.00		47	2.051	28 0	35.45		32	1.389
56	20.45		44	2.640	56 0	26.00		28	2.052

1. In comparing the results given by the angles of repose with the results given by the horizontal surfaces on similar kinds of cloth, there is a slight variation.

2. The second series of experiments afford no measure of comparison, from the inadequacy of the weights of 10lbs. being unable to give motion to the upper surface, 13lbs. 8oz. gives an approximation.

3. The less the weight, the greater the angle of repose.

4. Increase of surface produces a very great increase in the angles of repose.
The times very variable, diminish with increase of weight.

5. Velocities likewise variable.

Table IV. On the Friction of different Woods two square inches surface.

Weight on surface.	Weight required to move it.	Proportion.	Weight per square inch.	Average.	Weight on surface.	Weight required to move it.	Proportion.	Weight per square inch.	Average.
Red Teak on Red Teak.					American live Oak on American live Oak.				
cwt.	lbs. oz.		cwt. qrs.		cwt.	lbs. oz.		cwt. qrs.	
½	6 14	8.14	0 1		½	7 15	7.05	0 1	
1	14 2	7.92	0 2		1	14 13	7.56	0 2	
2	23 3	9.66	1 0		2	25 15	8.63	1 0	
3	38 1	8.82	1 2		3	36 11	9.15	1 2	
4	52 3	8.58	2 0		4	55 11	8.04	2 0	
5	64 2	8.73	2 2		5	70 3	7.97	2 2	
6	71 12	9.36	3 0	8.82	6	86 3	7.79	3 0	7.65
7	84 3	9.31	3 2		7	109 7	7.16	3 2	
8	90 8	9.90	4 0		8	128 4	6.98	4 0	
9	120 11	8.35	4 2		9	140 3	7.19	4 2	
10	126 5	8.86	5 0		10	154 1	7.26	5 0	
11	141 15	8.67	5 2		11	162 14	7.56	5 2	
12	154 3	8.71	6 0		12	187 5	7.17	6 0	
13	170 10	8.53	6 2						
Pine on Pine.									
cwt.	lbs. oz.		cwt. qrs.						
½	16 3	3.33	0 1						
1	27 14	4.01	0 2	3.40					
2	68 4	3.27	1 0						
3	111 5	3.01	1 2						

Experiments on the Friction of different Woods two square inches surface.

Black Beech on Black Beech.

Weight on surface.	Weight required to move it.		Proportion.	Weight per square inch.		Average.
cwt.	lbs.	oz.		cwt.	qrs.	
½	8	6	6.68	0	1	
1	15	5	7.31	0	2	
2	28	0	8.00	1	0	
3	45	3	7.43	1	2	
4	69	7	6.45	2	0	
5	83	3	6.73	2	2	7.13
6	100	4	6.70	3	0	
7	115	11	6.77	3	2	
8	124	10	7.18	4	0	
9	132	3	7.62	4	2	
10	148	11	7.53	5	0	

Norway Oak on Norway Oak.

Weight on surface.	Weight required to move it.		Proportion.	Weight per square inch.		Average.
cwt.	lbs.	oz.		cwt.	qrs.	
½	8	3	6.83	0	1	
1	14	5	7.82	0	2	
2	26	4	8.53	1	0	
3	41	3	8.17	1	2	
4	56	7	7.93	2	0	7.67
5	67	3	8.33	2	2	
6	80	4	8.37	3	0	
7	102	0	7.68	3	2	
8	164	3	5.45	4	0	

English Oak on English Oak.

Weight on surface.	Weight required to move it.		Proportion.	Weight per square inch.		Average.
cwt.	lbs.	oz.		cwt.	qrs.	
½	7	0	8.00	0	1	
1	15	0	7.46	0	2	
2	29	3	7.67	1	0	
3	43	2	7.79	1	2	7.83
4	55	0	8.14	2	0	
5	70	3	7.97	2	2	

Hornbeam on Hornbeam.

Weight on surface.	Weight required to move it.		Proportion.	Weight per square inch.		Average.
cwt.	lbs.	oz.		cwt.	qrs.	
½	8	10	6.49	0	1	
1	16	3	6.91	0	2	
2	30	5	7.38	1	0	
3	46	11	7.19	1	2	
4	65	5	6.85	2	0	6.57
5	83	1	6.74	2	2	
6	105	2	6.39	3	0	
7	167	3	4.68	3	2	

Elm on Elm.

Weight on surface.	Weight required to move it.		Proportion.	Weight per square inch.		Average.
cwt.	lbs.	oz.		cwt.	qrs.	
½	10	0	5.60	0	1	
1	22	1	5.07	0	2	
2	35	5	6.34	1	0	
3	53	2	6.32	1	2	
4	72	3	6.20	2	0	5.86
5	87	11	6.38	2	2	
6	108	4	6.20	3	0	
7	145	3	5.39	3	2	
8	168	11	5.31	4	0	

Honduras Mahogany on Honduras Mahogany.

Weight on surface.	Weight required to move it.		Proportion.	Weight per square inch.		Average.
cwt.	lbs.	oz.		cwt.	qrs.	
½	12	7	4.50	0	1	
1	26	0	4.30	0	2	
2	39	3	5.71	1	0	
3	59	5	5.66	1	2	
4	74	7	6.01	2	0	
5	92	3	6.07	2	2	
6	107	6	6.25	3	0	5.96
7	118	2	6.63	3	2	
8	136	4	6.57	4	0	
9	154	1	6.54	4	2	
10	171	0	6.54	5	0	
11	182	3	6.76	5	2	

Yellow Deal on Yellow Deal.

Weight on surface.	Weight required to move it.		Proportion.	Weight per square inch.		Average.
cwt.	lbs.	oz.		cwt.	qrs.	
½	19	7	2.88	0	1	
1	37	9	2.98	0	2	
2	76	3	2.94	1	0	
3	113	0	2.97	1	2	2.88
4	147	13	3.03	2	0	
5	224	0	2.50	2	2	

White Deal on White Deal.

Weight on surface.	Weight required to move it.		Proportion.	Weight per square inch.		Average.
cwt.	lbs.	oz.		cwt.	qrs.	
½	18	12	2.98	0	1	
1	29	5	3.82	0	2	3.81
2	48	3	4.94	1	0	

Table V.

Experiments on the Friction of two square inches surface of Wood at different angles of elevation.

Weight on surface.	Moved at degrees.	Time in descending 11 inches.	Proportion.	Weight on surface.	Moved at degrees.	Time in descending 11 inches.	Proportion.
Red Teak on Red Teak.				American live Oak on Red Teak.			
lbs.	° ′	sec.		lbs.	° ′	sec.	
10	8 00	18	7.116	10	9 00	22	6.314
20	7 45	15	7.348	20	8 00	24	7.116
28	7 15	20	7.861	28	8 30	20	6.691
56	7 00	16	8.144	56	7 45	25	7.348
Black Beech on Black Beech.				Norway Oak on Norway Oak.			
lbs.	° ′	sec.		lbs.	° ′	sec.	
10	8 15	20	6.897	10	8 00	19	7.116
20	7 20	17	7.770	20	7 30	20	7.596
28	7 40	19	7.429	28	7 00	20	8.144
56	6 40	21	8.556	56	6 20	25	9.010
English Oak on English Oak.				Elm on Elm.			
lbs.	° ′	sec.		lbs.	° ′	sec.	
10	9 30	17	5.976	10	11 40	19	4.843
20	8 30	17	6.691	20	10 30	18	5.396
28	7 40	18	7.429	28	10 00	19	5.671
56	7 30	20	7.596	56	9 30	19	5.976
Hornbeam on Hornbeam.				Honduras Mahogany on Hornbeam.			
lbs.	° ′	sec.		lbs.	° ′	sec.	
10	10 00	20	5.671	10	12 00	22	4.705
20	9 15	21	6.140	20	12 30	21	4.511
28	8 30	20	6.691	28	11 45	21	4.808
56	8 15	19	6.897	56	11 20	23	4.990
Yellow Deal on Yellow Deal.				White Deal on White Deal.			
lbs.	° ′	sec.		lbs.	° ′	sec.	
10	15 00	10	3.732	10	18 00	10	3.078
20	17 00	9	3.271	20	12 30	11	4.511
Pine on Pine.							
lbs.	° ′	sec.					
10	16 00	14	3.488				
20	17 00	11	3.271				

REMARKS.—From the foregoing experiments it appears that there is a great deal of irregularity in the results.

Increase of pressure scarcely increasing the resistance. This may arise in some degree from the surfaces becoming condensed, and thus rendered less liable to abrasion. In some of the cases abrasion had already commenced, but it was not convenient to pursue the experiment further.

The soft woods present more resistance than the hard woods.

Yellow deal on yellow deal being the greatest.

Red teak on red teak the least.

According to Mr. Knowles of the Navy Office, F.R.S., the weight of the Prince Regent of 120 guns on the slips previous to launching, was 2400 tons; which, divided by the area of the sliding surface of her bilge-ways (equal to 149,184 square inches), gives a pressure of 36lbs. per square inch.

But the weight of the Salisbury of 58 guns on the slips, according to the area of her bilge-ways, was 44lbs. per square inch. Now, by the foregoing Table, the average force required to put in motion the three different kinds of oak, under a pressure of 56lbs. per inch, is about $\frac{1}{8}$th of the pressure, which proportion prevails even as high as 6cwt. per inch area: and by Table IX. we find that soft soap (the ingredient mostly used for diminishing the friction of bilge-ways under a pressure of 56lbs per inch,) gives about $\frac{1}{26}$th of the pressure for the friction. Hence the angle at which a building slip should be laid can be easily determined. Coulomb even makes 49lbs. per square inch, and $\frac{1}{27}$th for the pressure for hogslard.

The weight of the middle arch (of 151 feet 9 inches span) of the New London Bridge, together with the centres, is 4900 tons. This acting upon the surface of the striking wedges equal to 540 square feet, gives a pressure of 140lbs. per square inch. The angles of inclination of the wedges are equal to 8° 45′, and their surfaces are covered with sheets of copper well coated with tallow. On removing the check pieces, the wedges commenced gliding back slowly and uniformly by the gravity of the arch and centres, and the motion was checked and continued until the arch was left in equilibrio.

Plate V.

This apparatus was constructed both for brass and iron. The pivots were accurately turned, and the suspending slings loosely hung. The total space passed over did not exceed four inches and a half. The cord was of the best sash-line, and the pulley very sensible. The rigidity of the former and friction of the latter were accurately ascertained, by trials at different weights. The block was of cast iron accurately bored. The axle was allowed to have full play in the block, in order that no binding might take place. The space passed through was denoted by marks on the axle and block. The time by a seconds watch.

An improvement was afterwards made in the apparatus, by substituting a roller of cast iron working in a block, and having a cord wound round its surface so as to allow of a descent of the moveable weight of 21 feet.

Table VI.

Experiments on extent of surface with Metals.

Cast Iron on Cast Iron. Laid flat: Area of surface 44 inches. Laid edgewise: Area $6\frac{3}{4}$ inches.

Wt. to be moved. (lbs.)	Laid flat: Weight required to move it. (lbs.)	(oz.)	Proportion.	Weight to 1 inch of area. (lbs.)	(oz.)	Laid edgewise: Weight required to move it. (lbs.)	(oz.)	Proportion.	Weight to 1 inch of area. (lbs.)	(oz.)
14	2	2	6.58	0	5.09	2	4	6.20	2	1.1
24	3	3	7.53	0	8.72	3	11	6.50	3	8.8
36	4	14	7.38	0	13.10	5	14	6.12	5	5.3
48	6	8	7.38	1	1.40	7	10	6.30	7	1.7
60	8	4	7.27	1	5.80	9	8	6.30	8	14.2
72	10	0	7.20	1	10.20	11	7	6.29	10	10.6
84	11	10	7.23	1	14.50	13	5	6.31	12	7.1
96	13	12	6.98	2	2.90	15	5	6.27	14	3.5

Hard Brass on Cast Iron. Laid flat: Area of surface 48 inches. Laid edgewise: Area $7\frac{3}{4}$ inches.

Wt. to be moved. (lbs.)	Laid flat: Weight required to move it. (lbs.)	(oz.)	Proportion.	Weight to 1 inch of area. (lbs.)	(oz.)	Laid edgewise: Weight required to move it. (lbs.)	(oz.)	Proportion.	Weight to 1 inch of area. (lbs.)	(oz.)
14	1	14	7.4	0	$4\frac{2}{3}$	1	11	8.3	1	12
24	3	5	7.2	0	8	4	0	6.0	3	1
36	4	9	7.8	0	12	6	0	6.0	4	10
48	6	4	7.6	1	0	7	13	6.1	6	3
60	7	12	7.7	1	4	9	0	6.6	7	11
72	9	12	7.3	1	8	11	0	6.5	9	4
84	11	8	7.3	1	12	13	2	6.4	10	13
96	13	1	7.3	2	0	14	8	6.6	12	6

Yellow Brass on Cast Iron. Laid flat: Area of surface 44 inches. Laid edgewise: Area $6\frac{3}{4}$ inches.

Wt. to be moved. (lbs.)	Laid flat: Weight required to move it. (lbs.)	(oz.)	Proportion.	Weight to 1 inch of area. (lbs.)	(oz.)	Laid edgewise: Weight required to move it. (lbs.)	(oz.)	Proportion.	Weight to 1 inch of area. (lbs.)	(oz.)
14	1	15	7.22	0	5.09	2	1	6.79	2	1.1
24	3	7	6.98	0	8.72	3	8	6.85	3	8.8
36	5	6	6.70	0	13.10	5	1	7.11	5	5.3
48	7	3	6.67	1	1.40	6	10	7.24	7	1.7
60	9	3	6.53	1	5.80	9	3	6.53	8	14.2
72	11	5	6.36	1	10.20	10	5	6.98	10	10.6
84	13	5	6.30	1	14.50	13	12	6.10	12	7.1
96	15	13	6.07	2	2.90	15	1	6.37	14	3.5

Tin on Cast Iron. Laid flat: Area of surface 44 inches. Laid edgewise: Area $6\frac{3}{4}$ inches.

Wt. to be moved. (lbs.)	Laid flat: Weight required to move it. (lbs.)	(oz.)	Proportion.	Weight to 1 inch of area. (lbs.)	(oz.)	Laid edgewise: Weight required to move it. (lbs.)	(oz.)	Proportion.	Weight to 1 inch of area. (lbs.)	(oz.)
14	2	8	5.60	0	5.1	2	12	5.09	2	1.1
24	4	7	5.40	0	8.7	4	8	5.33	3	8.8
36	6	0	6.00	0	13.1	6	7	5.59	5	5.3
48	8	7	5.68	1	1.4	8	14	5.40	7	1.7
60	9	13	6.11	1	5.8	9	13	6.11	8	14.2
72	12	5	5.84	1	10.2	11	13	6.09	10	10.6
84	14	5	5.86	1	14.5	14	5	5.86	12	7.1
96	16	4	5.90	2	2.9	16	4	5.09	14	3.5

From the foregoing experiments it appears that the friction of

Cast iron upon cast iron laid flat, varies . . . . from 6.58 to 7.53
Cast iron upon cast iron laid edgewise, varies . . . . . . from 6.2 to 6.5
Of hard brass upon cast iron laid flat, varies . . . . . . from 7.2 to 7.8
Of hard brass upon cast iron laid edgewise, varies . . . . from 6.0 to 8.0
Of yellow brass upon cast iron laid flat, varies . . . . . from 6.09 to 7.22
Of yellow brass upon cast iron laid edgewise, varies . . . from 6.1 to 7.24
Of tin upon cast iron laid flat, varies . . . . from 5.4 to 6.11
Of tin upon cast iron laid edgewise, varies . . . . from 5.09 to 6.11

That the friction is nearly the same with cast iron and brass whether the load be applied on the broad side or on the narrow side of the plates, although the areas of the surfaces are to each other as 6.22 : 1.

That tin being a softer metal and more easily abraded: the friction increases when a load is applied above 8lbs. per square inch, but remains nearly the same with the broad side as with the narrow side. Generally speaking, the friction is less with the broad side than with the narrow side.

Table VII.

Experiments on the Friction of different Metals with the weights increased from 14lbs. to 192lbs.

Weight to be moved.	Weight required to move it.	Proportion.	Weight to 1 inch of area.	Weight to be moved.	Weight required to move it.	Proportion.	Weight to 1 inch of area.
Brass on Wrought Iron. Length $6\frac{3}{4}$ inches, Width $\frac{7}{8}$. Area 5.906.				Cast Iron on Cast Iron. Area 6.75.			
lbs.	lbs. oz.		lbs. oz.	lbs.	lbs. oz.		lbs. oz.
14	2 2	6.58	2 5.9	14	2 4	6.22	2 1.2
24	3 11	6.50	4 1.0	24	3 0	8.00	3 8.9
36	4 14	7.38	6 1.5	36	5 14	6.12	5 5.3
48	6 6	7.52	8 2.0	48	7 10	6.29	7 1.7
60	8 0	7.50	10 2.5	60	9 8	6.31	8 14.2
72	9 6	7.68	12 3.0	72	11 7	6.29	10 10.6
84	10 10	7.90	14 3.5	84	13 5	6.30	12 7.1
96	12 9	7.64	16 4.0	96	15 5	6.27	14 3.5
192	27 0	7.11	32 8.0				
Soft Steel on Wrought Iron. Area 5.906.				Brass sliding on Steel. Area 5.9.			
lbs.	lbs. oz.		lbs. oz.	lbs.	lbs. oz.		lbs. oz.
14	2 8	5.60	2 5.9	14	2 1	6.78	2 5.9
24	4 8	5.33	4 1.0	24	3 8	6.85	4 1.0
36	6 13	5.28	6 1.5	36	5 0	7.20	6 1.6
48	9 5	5.15	8 2.0	48	7 11	6.24	8 2.1
60	12 6	4.84	10 2.5	60	9 11	6.19	10 2.7
72	14 13	4.86	12 3.0	72	11 5	6.36	12 3.2
84	17 5	4.85	14 3.5	84	13 0	6.46	14 3.7
96	19 4	4.98	16 4.0	96	15 0	6.40	16 4.3
192	32 8	5.90	32 8.0	192	28 0	6.85	32 8.0
Brass sliding on Brass. Area 5.9.				Cast Iron on Wrought Iron. Area 5.9.			
lbs.	lbs. oz.		lbs. oz.	lbs.	lbs. oz.		lbs. oz.
14	2 10	5.33	2 5.9	14	2 4	6.22	2 5.9
24	3 8	6.85	4 1.0	24	4 2	5.81	4 1.0
36	6 5	5.70	6 1.6	36	6 2	5.87	6 1.6
48	8 4	5.81	8 2.1	48	7 12	6.19	8 2.1
60	10 3	5.88	10 2.7	60	9 8	6.31	10 2.7
72	12 0	6.00	12 3.2	72	11 5	6.36	12 3.2
84	14 0	6.00	14 3.7	84	13 13	6.08	14 3.7
96	16 0	6.00	16 4.3	96	17 0	5.64	16 4.3
192	44 8	4.31	32 8.0	192	33 8	5.73	32 8.0

Experiments on the Friction of different Metals with the weights increased from 14lbs. to 192lbs.

Cast Iron sliding on Soft Steel. Area 5.9.

Weight to be moved.	Weight required to move it.	Proportion.	Weight to 1 inch of area.
lbs.	lbs. oz.		lbs. oz.
14	2 2	6.59	2 5.9
24	3 10	6.62	4 1.0
36	5 7	6.62	6 1.6
48	7 2	6.73	8 2.1
60	9 8	6.31	10 2.7
72	11 9	6.22	12 3.2
84	13 9	6.19	14 3.7
96	15 5	6.26	16 4.3
192	32 0	6.00	32 8.0

Soft Steel on Soft Steel. Area 5.9.

Weight to be moved.	Weight required to move it.	Proportion.	Weight to 1 inch of area.
lbs.	lbs. oz.		lbs. oz.
14	2 0	7.00	2 5.9
24	3 7	6.98	4 1.0
36	5 4	6.85	6 1.6
48	6 13	7.04	8 2.1
60	8 11	6.90	10 2.7
72	10 5	6.98	12 3.2
84	12 2	6.92	14 3.7
96	13 12	6.98	16 4.3
192	31 8	6.09	32 8.0

Wrought Iron on Wrought Iron. Area 5.9.

Weight to be moved.	Weight required to move it.	Proportion.	Weight to 1 inch of area.
lbs.	lbs. oz.		lbs. oz.
14	2 1	6.78	2 5.9
24	3 13	6.29	4 1.0
36	5 12	6.26	6 1.6
48	7 2	6.73	8 2.1
60	9 8	6.31	10 2.7
72	11 6	6.32	12 3.2
84	12 15	6.49	14 3.7
96	14 3	6.76	16 4.3
192	27 0	7.11	32 8.0

Tin sliding on Wrought Iron. Area 5.9.

Weight to be moved.	Weight required to move it.	Proportion.	Weight to 1 inch of area.
lbs.	lbs. oz.		lbs. oz.
14	2 10	5.33	2 5.9
24	4 6	5.48	4 1.0
36	6 8	5.53	6 1.6
48	7 14	6.09	8 2.1
60	9 13	6.11	10 2.7
72	11 13	6.09	12 3.2
84	13 15	6.02	14 3.7
96	15 13	6.07	16 4.3
192	32 8	5.90	32 8.0

Tin sliding on Tin. Area 5.9.

Weight to be moved.	Weight required to move it.	Proportion.	Weight to 1 inch of area.
lbs.	lbs. oz.		lbs. oz.
14	3 10	3.86	2 5.9
24	7 8	3.20	4 1.0
36	9 8	3.78	6 1.6
48	12 13	3.74	8 2.1
60	17 7	3.44	10 2.7
72	22 2	3.25	12 3.2
84	28 8	2.94	14 3.7
96	36 0	2.66	16 4.3
192	66 8	2.88	32 8.0

Cast Iron on Hard Brass. Area 7.75.

Weight to be moved.	Weight required to move it.	Proportion.	Weight to 1 inch of area.
lbs.	lbs. oz.		lbs. oz.
14	1 11	8.29	1 12.9
24	4 0	6.00	3 1.5
36	6 0	6.00	4 10.3
48	7 13	6.14	6 3.0
60	9 0	6.66	7 11.8
72	11 0	6.54	9 4.6
84	13 2	6.40	10 13.4
96	14 8	6.62	12 6.1

Brass on Cast Iron. Area 6.75.

Weight to be moved.	Weight required to move it.	Proportion.	Weight to 1 inch of area.
lbs.	lbs. oz.		lbs. oz.
14	2 1	6.78	2 1.2
24	3 8	6.85	3 8.9
36	5 1	7.11	5 5.3
48	6 10	7.24	7 1.7
60	9 3	6.53	8 14.2
72	10 5	6.98	10 10.6
84	13 12	6.10	12 7.1
96	15 1	6.37	14 3.5

Tin sliding on Cast Iron. Area 6.75.

Weight to be moved.	Weight required to move it.	Proportion.	Weight to 1 inch of area.
lbs.	lbs. oz.		lbs. oz.
14	2 12	5.09	2 1.2
24	4 8	5.33	3 8.9
36	6 7	5.59	5 5.3
48	8 14	5.40	7 1.7
60	9 13	6.11	8 14.2
72	11 13	6.09	10 10.6
84	14 5	5.86	12 7.1
96	16 4	5.90	14 3.5

Table VIII.

A Table showing the Power required to move a Weight progressively increased until the metals abrade each other.

Wrought Iron on Wrought Iron. Area 6 inches.

Weight to be moved.	Weight required to move it.		Proportion.	Weight to 1 inch of area.
cwt.	cwt.	qrs.		cwt.
10	2	2	4.00	1.66
12	3	1	3.69	2.00
14	4	0	3.50	2.33
16	4	3	3.36	2.66
18	5	2.5	3.20	3.00
20	7	0	2.85	3.33
22	8	1	2.66	3.66
24	9	0	2.66	4.00
26	10	1	2.53	4.33
28	11	1	2.48	4.66
30	12	1	2.44	5.00

Wrought Iron on Cast Iron. Area 6 inches.

Weight to be moved.	Weight required to move it.		Proportion.	Weight to 1 inch of area.
cwt.	cwt.	qrs.		cwt.
10	2	3	3.63	1.66
12	3	2	3.42	2.00
14	4	2	3.11	2.33
16	5	1	3.04	2.66
18	6	0	3.00	3.00
20	7	0	2.85	3.33
22	7	3	2.83	3.66
24	8	3	2.74	4.00
26	9	2	2.73	4.33
28	10	1	2.73	4.66
30	11	0	2.72	5.00
32	11	3	2.72	5.33
34	12	2	2.72	5.66
36	13	2	2.66	6.00
38	16	2	2.30	6.33

Steel on Cast Iron. Area 6 inches.

Weight to be moved.	Weight required to move it.		Proportion.	Weight to 1 inch of area.
cwt.	cwt.	qrs.		cwt.
10	3	0	3.33	1.66
12	4	0	3.00	2.00
14	4	3	2.94	2.33
16	5	2	2.90	2.66
18	6	1	2.88	3.00
20	7	0	2.85	3.33
22	7	3	2.83	3.66
24	8	2	2.82	4.00
26	9	1	2.81	4.33
28	10	0	2.80	4.66
30	10	3	2.79	5.00
32	11	2	2.78	5.33
34	12	2	2.72	5.66
36	14	2	2.48	6.00

Brass on Cast Iron. Area 6 inches.

Weight to be moved.	Weight required to move it.			Proportion.	Weight to 1 inch of area.
cwt.	cwt.	qrs.	lbs.		cwt.
10	2	1	00	4.44	1.66
12	2	2	14	4.57	2.00
14	3	0	00	4.66	2.33
16	3	1	14	4.74	2.66
18	3	3	14	4.64	3.00
20	4	0	14	4.84	3.33
22	4	2	00	4.88	3.66
24	5	0	00	4.80	4.00
26	5	3	00	4.52	4.33
28	6	1	00	4.48	4.66
30	7	0	00	4.28	5.00
32	7	2	00	4.26	5.33
34	8	0	00	4.25	5.66
36	8	1	14	4.29	6.00
38	8	3	14	4.28	6.33
40	9	1	14	4.26	6.66
42	9	3	00	4.30	7.00
44	12	0	00	3.66	7.33

Appendix to TABLES VII. and VIII.

TABLE showing the comparative amount of Friction of different Metals under an average pressure of from 54.25lbs. to 69.55lbs. as calculated from the foregoing experiments.

Description of Metals.	Average Weight.	Proportion.	Weight per Square Inch Area.
	lbs.		lbs. oz.
Brass on wrought iron	69.55	7.312	11 12.4
Steel upon steel	69.55	6.860	11 12.5
Brass upon cast iron	54.25	6.745	8 0.5
Brass upon steel...............	69.55	6.592	11 12.5
Hard brass upon cast iron......	54.25	6.581	6 15.9
Wrought iron on wrought iron..	69.55	6.561	11 12.5
Cast iron upon cast iron	54.25	6.475	8 0.5
Cast iron upon steel	69.55	6.393	11 12.5
Cast iron upon wrought iron....	69.55	6.023	11 12.5
Tin upon wrought iron	69.55	5.846	11 12.5
Brass upon brass	69.55	5.764	11 12.5
Tin upon cast iron............	54.25	5.671	8 0.5
Steel upon wrought iron	69.55	5.198	11 12.4
Tin upon tin	69.55	3.305	11 12.5

Remarks on TABLES VII. and VIII.

1. From the preceding experiments it appears:—that the friction of metals varies with their hardness.

2. That the hard metals have less friction than the soft ones.

3. That without unguents and within the limits of 32lbs 8oz. per square inch, the friction of hard metals against hard metals may very generally be estimated at about one-sixth of the pressure.

4. That within the limits of their abrasion the friction of metals is nearly alike.

5. That from 1.66cwt. per square inch to upwards of 6cwt. per square inch, the resistance increases in a very considerable ratio, being the greatest with steel on cast iron, and the least with brass on wrought iron, their limits being as 30, 36, 38, and 44cwt. An experiment was made with a weight of 10 tons per inch on hardened steel, which abraded.

The remarkable property of steel in hardening, and its power to resist abrasion, render it preferable to every other substance yet discovered in reducing the friction of delicate instruments, as is exemplified in the different experiments on the pendulum, and the assay and other balances recently introduced at His Majesty's Mint and the Bank of England.

The experiments of Messrs. CAVENDISH and HATCHETT in the years 1798 and 1801 at His Majesty's Mint on the alloys, specific gravity, and comparative wear of gold coin by friction, likewise prove that friction and abrasion were less in the hard than soft metals. Philosophical Transactions for 1803, Part I.

Table IX.

Experiments on the Friction of Axles without and with Unguents.

Weight on Axle.	Weight required to move it.	Time.	Proportion.	Space passed over.
Gun Metal on Cast Iron.				
cwt.	lbs. oz.	sec.		
1	16 0	90	7.00	4½ inches.
2	30 0	,,	7.46	
3	44 0	,,	7.63	
4	60 12	,,	7.37	
5	112 0	80	5.00	
6	134 0	90	5.01	
7	After remaining 12 hrs. it took to move it 154 0	,,	5.09	
8	175 0	,,	5.12	
9	200 0	,,	5.04	
10	238 0	,,	4.70	
Yellow Brass on Cast Iron.				
cwt.	lbs. oz.	sec.		
10	272 0	90	4.11	4½ inches.
Cast Iron on Cast Iron.				
cwt.	lbs. oz.	sec.		
10	173 8	90	6.45	4½ inches.
11	228 0		5.40	
Cast Iron on Cast Iron with Black-lead.				
cwt.	lbs. oz.	sec.		
11	161 0	90	7.65	4½ inches.
Gun Metal on Cast Iron with Black-lead.				
cwt.	lbs. oz.	sec.		
11	170 0	90	7.24	4½ inches.
Yellow Brass on Cast Iron with Black-lead.				
cwt.	lbs. oz.	sec.		
1	14 12	90	7.59	4½ inches.
2	31 4		7.16	
3	47 8		7.07	
4	65 8		6.83	
5	84 0		6.66	
11	181 0		6.80	
Gun Metal on Cast Iron with Oil.				
cwt.	lbs. oz.	sec.		
11	218 8	90	5.63	4½ inches.

Experiments on the Friction of Axles without and with Unguents.

Weight on Axle.	Weight required to move it.	Time.	Proportion.	Space passed over.
Yellow Brass on Cast Iron.				
cwt.	lbs. oz.	sec.		
½	1 8	90	37.33	4½ inches.
1	3 8		32.00	
2	7 0		32.00	
3	16 8		20.36	
4	24 8		18.28	
5	29 4		19.14	
10	193 8		5.78	
11	200 12		6.13	
Cast Iron on Cast Iron.				
cwt.	lbs. oz.	sec.		
10	131 1	90	8.54	4½ inches.
11	140 0		8.80	
Cast Iron on Cast Iron with Hogslard.				
cwt.	lbs. oz.	sec.		
10	117 4	90	9.55	4½ inches.
Yellow Brass on Cast Iron.				
cwt.	lbs. oz.	sec.		
½	1 10	90	34.46	4½ inches.
1	3 1		36.57	
2	7 8		29.86	
3	23 0		14.60	
4	43 0		10.41	
5	47 8		11.78	
10	120 8		9.29	
Gun Metal on Cast Iron with Hogslard.				
cwt.	lbs. oz.	sec.		
10	130 4	90	8.59	4½ inches.
Yellow Brass on Cast Iron with Anti-Attrition Composition.				
cwt.	lbs. oz.	sec.		
1	7 8	90	14.93	4½ inches.
2	9 0		24.88	
3	10 8		32.00	
4	12 8		35.84	
5	14 8		38.62	
After remaining 41 hrs. in a state of rest with 10	it took 190 0		5.89	
Fresh composition being applied 10	it took only 23 8		47.65	
10	again 20 0		56.00	

Experiments on the Friction of Axles without and with Unguents.

Weight on Axle.	Weight required to move it.	Time.	Proportion.	Space passed over.
	Yellow Brass on Cast Iron with Tallow.			
cwt.	lbs. oz.			
1	3 1		36.57	
2	5 12	sec.	38.95	
3	8 5	90	40.42	4½ inches.
4	11 1		40.49	
5	13 12		40.72	
	Yellow Brass on Cast Iron with Soft-soap.			
cwt.	lbs. oz.			
½	2 2		26.35	
1	3 8		32.00	
2	6 0		37.33	
3	9 8	90	35.36	4½ inches.
4	12 12		35.13	
5	14 12		37.96	
	Yellow Brass on Cast Iron with Soft-soap and Black-lead.			
cwt.	lbs. oz.			
½	5 8		10.18	
1	9 3		12.19	
2	12 1		18.56	
3	14 4	90	23.57	4½ inches.
4	19 8		22.97	
5	23 8		23.82	

Remarks on the experiments without Unguents.

From the foregoing experiments it appears,—

That when gun metal without unguents is loaded with variable weights of from 1 to 10 cwt., friction varies nearly in the proportion of $\frac{1}{7.63}$ to $\frac{1}{4.70}$ of the pressure.

That length of time scarcely affects it.

That friction increased when yellow brass was tried.

That friction decreased when cast iron was tried.

That friction diminished still more when black-lead was used between the three different metals.

Remarks on the experiments with Unguents.

That gun metal on cast iron, with oil intervening and a weight of 10 cwt., amounted to $\frac{1}{5.63}$ of the pressure.

That when the insistent weights were diminished, the friction with oil was reduced to $\frac{1}{37.33}$, but increased with an increase of weight.

That cast iron on cast iron, under similar circumstances, showed less friction.

That the friction of cast iron on cast iron was still further diminished by hogslard.

That the friction of yellow brass on cast iron was increased by light weights and diminished by heavy weights, perhaps from being less fluid and sensible in the one case, and more capable of preventing the contact of metals in the other.

That gun metal on cast iron with hogslard gave less friction than with oil.

That yellow brass on cast iron with anti-attrition composition of black-lead and hogslard, increased friction with light weights, and greatly diminished it with heavy weights, showing extremely irregular results.

That yellow brass on cast iron with tallow gave the least friction, and may therefore be considered the best substance under the circumstances tried.

That yellow brass on cast iron with soft-soap gave the second best result, being superior to oil.

That yellow brass on cast iron with soft-soap and black-lead gave the worst result, diminishing the friction in the inverse ratio of the weight.

Conclusion.—That the diminution of friction by unguents varies as the insistent weights and natures of the unguents; the lighter the weight the finer and more fluid should be the unguents, and vice versa.

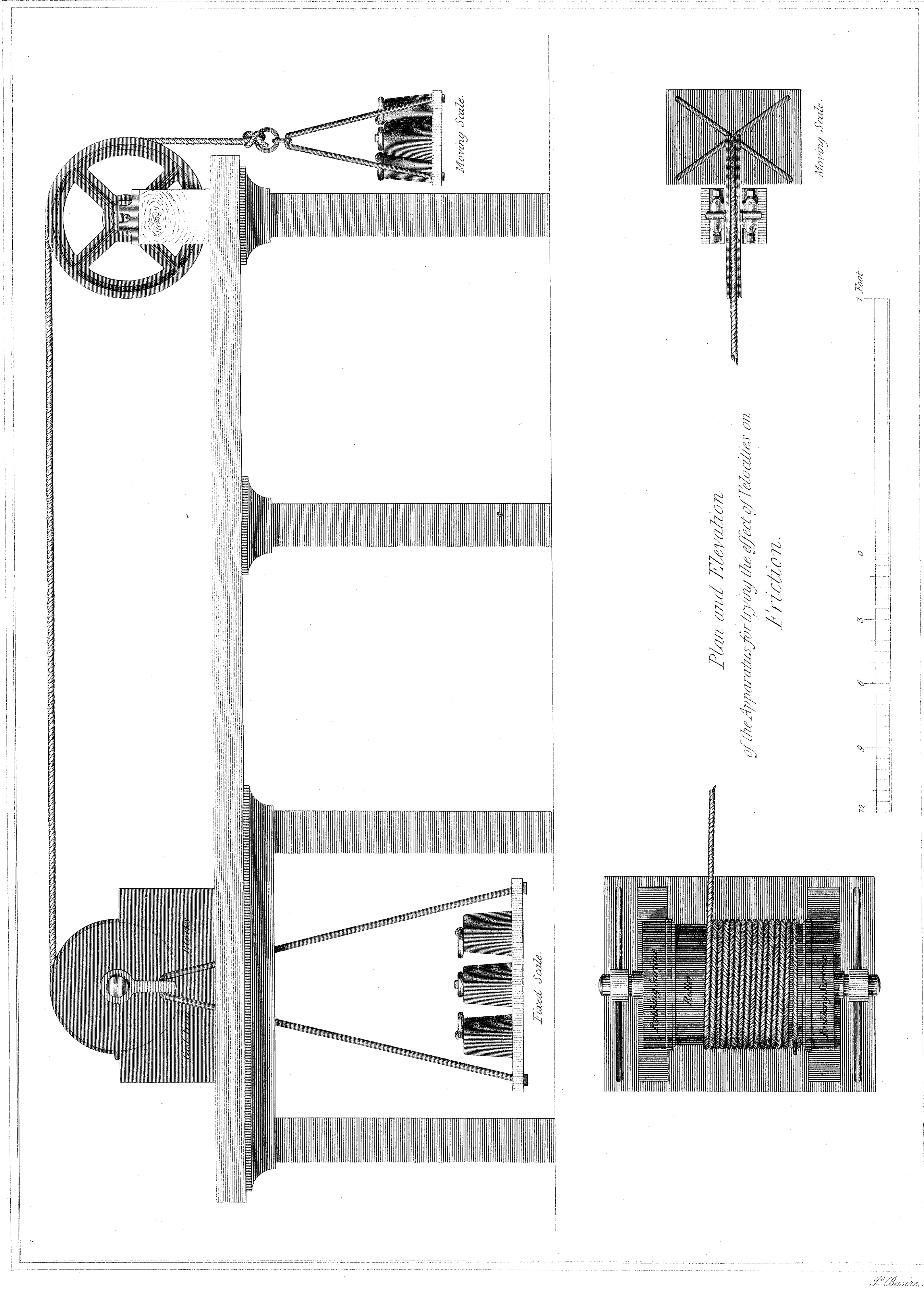
Table X.

Experiments on Velocities in Friction.

A cast iron Cylinder with two bearings of one inch wide, six inches diameter, with two side collars one-eighth of an inch deep; a rope of three-eighths of an inch diameter wound round the cylinder. Bearing surface $12\frac{1}{2}$ square inches. (Plate V.)

Without Oil.

Weight in roller scale. lbs. oz.	Weight required to move the roller. lbs. oz.	Height fallen.	Time in falling. Seconds.	Remarks.	Proportion.
348 8	112 0			Four trial experiments made by decreasing weight; very unsteady motion.	3.11
300 0	112 0		5		2.67
280 0	114 0		7*	* Began to grind.	2.45
280 0	114 0		7†	† Grinding increasing with stopping.	2.45
280 0	228 0		$4\frac{1}{2}$		1.22
224 8	112 0		6		2.00
224 8	112 0		$4\frac{1}{2}$		2.00
174 8	58 0		4		3.00
174 8	58 0		4		3.00
174 8	116 0	21 feet	2		1.50
174 8	116 0		2		1.50
160 8	56 0		7		2.86
160 8	56 0		8		2.86
66 8	28 0		8		2.37
62 8	22 0		4		2.84
62 8	22 0		4		2.84
62 8	44 0		$2\frac{1}{2}$		1.42
62 8	44 0		$2\frac{1}{2}$		1.42
62 8	44 0		$2\frac{1}{2}$		1.42



Plan and Elevation of the Apparatus for trying the effect of Velocities on Friction.

Js. Basire, sc.

Experiments with Oil.					
Weight in roller scale.	Weight required to move the roller.	Height fallen.	Time in falling.	Remarks.	Proportion.
lbs. oz.	lbs. oz.		1st half. 2nd half. Seconds.		
62 8	7 0	21 feet	12		8.92
62 8	7 0		17½		8.92
62 8	7 0		11 22		8.92
62 8	7 0		9 18		8.92
62 8	7 0		8 16		8.92
62 8	7 0		8 16	Found the velocity too great; made an addition of 21½lbs. making ¾cwt. in the fixed scale, which brought it regular.	8.92
62 8	7 0		8½ 17		8.92
62 8	14 0		3 5 }		4.46
62 8	14 0		3 5 }		4.46
62 8	14 0		3 5 }		4.46
84 0	14 0		3½ 7	This weight produced a regular velocity.	6.00
84 0	14 0		3½ 7		6.00
84 0	14 0		3½ 7		6.00
Experiments with Tallow.					
lbs. oz.	lbs. oz.		Seconds.		
272 8	42 0	21 feet	14 28		6.48
272 8	42 0		6½ 13		6.48
272 8	42 0		6½ 13		6.48
272 8	42 0		7½ 14		6.48

REMARKS.—The irregularity of the resistances observed in the first seven experiments arose from the impartial contact and consequent grinding or abrading of the surfaces. The roller having attained its bearing, and the weight in the roller-scale being diminished, the irregularity ceased, especially when oil and tallow were used.

From the result of these experiments it will be seen, that friction did not increase with an increase of velocity. The time in falling the whole height of twenty-one feet being double the time in falling half the height. These experiments were likewise illustrated (but not so satisfactorily,) by a machine somewhat similar to that of Mr. Roberts.—The pulley was sufficiently distant from the roller to render the angle of tension imperceptible.

Appendix to Table X.

Friction of the cord and weight on the axles of the iron rollers, to be deducted from the foregoing experiments.		
Weight in each end.	Total of weights.	Weight required to overcome the friction of the cord.
lbs.	lbs.	lbs. oz.
56	112	4 8
112	224	7 0
168	336	11 4
224	448	14 0

Remarks on Table X.

The deductions to be made for the rigidity of the cord used in the foregoing experiments under variable weights, as shown in the second and third columns, are nearly as the weights simply, and are applicable to most of the cases in Table IX.

Table XI. Experiments on the friction of Ice.

A block of ice eighteen inches long and two inches thick, as free as possible from air-bubbles, was accurately prepared so as to present a smooth, flat surface, and was then fixed on the frame. A piece of the same block of ice, but of smaller dimensions, was accurately prepared, and made to glide with its flat surface over the bottom block, and a fine flexible silken cord attached to it as in the former experiments.

The weights in the first column indicate the insistent weights, and the weight in the second column the moveable weights. The experiments were made when the temperature of the atmosphere was about 28 degrees of Fahr.

Sixteen inches surface.			With two skates $4\frac{1}{2}$ inches long, by $\frac{3}{16}$ wide, in surface in each.		
Weight on surface.	Weight required to move it.	Proportion.	Weight on surface.	Weight required to move it.	Proportion.
lbs. oz.	lbs. oz.		lbs. oz.	lbs. oz.	
1 8	0 3	8.00	1 8	0 1	24.00
4 0	0 5	12.80	4 0	0 3	21.33
16 0	0 10	25.60	16 0	0 7	36.57
36 0	1 0	36.00	36 0	0 15	38.40
64 0	1 6	46.54	64 0	1 2	56.88
81 0	1 13	44.68	81 0	1 10	49.84
144 0	2 9	56.19	144 0	2 1	69.81
After remaining 16 hours.					
lbs. oz.	lbs. oz.				
1 8	0 3	8.00			
4 0	0 6	10.66			
16 0	0 15	17.06			
36 0	1 9	23.04			
64 0	3 2	20.48			
81 0	4 0	20.25			
144 0	6 5	22.81			

REMARKS.—From the foregoing experiments it appears, that with ice on ice, friction diminishes with an increase of weight, but does not seem to observe any regular law with regard to that increase.

Table XII. Experiments on the Friction of Hide Leather.

Twelve pieces of hide leather were placed parallel to each other in a wooden box, with one side loose so as to admit of being adjusted according to the number of pieces of leather; a bolt was then passed through the whole, and a nut screwed on the end of the bolt so as to compress the pieces of leather together and permit them to act on edge as one uniform surface; which surface was increased or diminished by putting in or taking out some of the pieces of leather and screwing up the nut as before.

Friction of 9 square inches of leather soaked in water, moving over a plate of iron.

7 lbs. barely kept in motion 36 lbs. after starting with the hand. After remaining 5 minutes it took to start it 29 lbs. 28 lbs. barely kept in motion 64 lbs. after starting it, and after remaining one minute it took 42 lbs. to start it.

Surface $1\frac{1}{2}$ by 3 inches, equal to $4\frac{1}{2}$ inches area.

$6\frac{1}{2}$ lbs. barely kept in motion 36 lbs. after starting it. After remaining 5 minutes it took 21 lbs. to start it. 21 lbs. barely kept in motion 64 lbs. after starting it. After remaining 5 minutes it took 38 lbs. to start it.

Friction of Hide Leather moving dry over a surface of Cast Iron.

Weight on Surface.	Weight required to move it.	Proportion.	Space passed over.	Time.	Weight per inch Area.	Weight on Surface.	Weight required to move it.	Proportion.	Space passed over.	Time.	Weight per inch Area.
Area of surface 9 square inches.						Area of surface $4\frac{1}{2}$ square inches.					
lbs.	lbs. oz.		inches.	sec.	lbs.	lbs.	lbs. oz.		inches.	sec.	lbs.
6	1 8	4.0			.66	6	1 2	5.33			1.33
7	1 12	4.0			.77	7	1 5	5.33			1.55
8	2 0	4.0	18	18	.88	8	1 9	5.12	18	18	1.77
36	8 12	4.1			4.00	36	7 3	5.00			8.00
49	12 0	4.0			5.44	49	9 5	5.26			10.88
64	16 0	4.0			7.11	64	13 10	4.69			14.22
Area of surface $6\frac{3}{4}$ square inches.						Area of surface $2\frac{1}{4}$ square inches.					
lbs.	lbs. oz.		inches.	sec.	lbs.	lbs.	lbs. oz.		inches.	sec.	lbs.
6	1 4	4.80			.88	6	1 1	5.64			2.66
7	1 8	4.66			1.03	7	1 3	5.89			3.11
8	1 12	4.57	18	18	1.18	8	1 8	5.33	18	18	3.55
36	7 4	4.96			5.33	36	7 1	5.09			16.00
49	11 0	4.45			7.25	49	9 1	5.40			21.77
64	14 0	4.57			9.48	64	13 2	4.87			28.44

REMARKS.—The friction of hide leather soaked in water appears to be greatly increased by time and weight. This circumstance explains the enormous friction evinced in the pistons of pumps when first put in motion. When the leather is not soaked, the resistance varies from one $\frac{1}{4}$th to nearly one $\frac{1}{6}$th of the pressure, and is diminished (cæteris paribus) by a diminution of surface.

XIII. On the Friction of Stones.

RONDELET found that stones well dressed required angles of from 28° to 36° before they commenced gliding*. PERRONET observed them to vary from 39° to 40°†. The granite voussoirs of the arches of the New London Bridge having their beds well faced and dressed without mortar, generally commence gliding at angles of from 33° to 34°. But with a bed of fresh and finely ground mortar interposed, the pressure on the centring commences at angles of from 25° to 26°. In other cases of arches where sandstones, such as Bramley Fall and Whitby were employed, and their beds faced and dressed as usual, the angle of gliding was found to vary from 35° to 36°. But with mortar interposed the angle generally varied from 33° to 34°.

It results from these and other experiments, that friction, by absorbing part of the horizontal thrust, is a most powerful assistant in maintaining the equilibrium of arches, and enables us to determine with something like precision the allowances due to theory.

In general, stones which have a fine grain and uniform texture, and are sonorous and heavy, resist abrasion in proportion to their hardness; and in some experiments of MORISOT‡, granite resists abrasion twelve times more than lias, whilst the former only possesses a repulsive power three times greater than the latter.

The experiments of BOISTARD give 0.78 for the friction of hard calcareous stones§.

XIV. On the Friction of Machines.

1. 21 cwt. (suspended at each extremity of a chain passing over two cast iron sheaves of 2 feet diameter with wrought iron axles, working in brass bearings oiled, and 12 feet 10 inches apart) was disturbed by 3 cwt. or $\frac{1}{14}$th of the total weight. Another double purchased crane indicated $\frac{1}{9}$th.

2. A double purchased crane having a weight of 7057lbs. suspended to it indicated 7.62 for the friction. Another double purchased crane indicated $\frac{1}{9}$th.

* L'Art de Batir. Tome iii.

† Mémoire sur le Cintrement et Décintrement des Ponts.

‡ MORISOT, Tome iv.

§ Recueil d'Experiences et d'Observations &c.

In an experiment made on one of the corn mills recently erected for His Majesty's victualling department at Deptford, it required $\frac{1}{10}$ of the weight of the mass to overcome the inertia and friction of the bearings and tangential surfaces. In this instance the pressures of the different parts of the machine varied from 28lbs. to 8 cwt. per inch area, and the velocities of the surfaces from 50 feet to 120 feet per minute.

REMARKS.—It has been customary to deduct one fourth of the power expended for friction. This allowance may maintain in machines newly set in motion. When the bearings have been equalized and the rubbing surfaces extended by the abrasion of the irregularities, the friction will be diminished and the movements of the machine be more steady. But when the bearings are properly proportioned to the weight of the parts of a machine, and their surfaces kept from contact by unguents, a much less allowance may be made.

Several experiments were made by giving motion to a fly wheel and a grindstone of known weights and revolutions in a given time, and then counting the revolutions after being detached from the power; but owing to the resistance of the air, and the bearings being too small, the results were unsatisfactory.

TABLE XV. Showing the amount of friction (without unguents) of different substances, the insistent weight being 36lbs. and within the limits of abrasion of the softest substance.

	Parts of the whole weight.		Parts of the whole weight.
Steel on ice	69.81	Cast iron on wrought iron	5.87
Ice on ice	36.00	Brass on brass	5.70
Hard wood on hard wood	7.73	Tin on cast iron	5.59
Brass on wrought iron	7.38	Tin on wrought iron	5.53
Brass on cast iron	7.11	Soft steel on wrought iron	5.28
Brass on steel	7.20	Leather on iron	4.00
Soft steel on soft steel	6.85	Tin on tin	3.78
Cast iron on steel	6.62	Granite on granite	3.30
Wrought iron on wrought iron	6.26	Yellow deal on yellow deal	2.88
Cast iron on cast iron	6.12	Sand-stone on sand-stone	2.75
Hard brass on cast iron	6.00	Woollen cloth on woollen cloth	2.30

These results are collected from the different Tables, but the comparison may be made by selecting other values within the limits of abrasion for a minimum.

General Conclusions.

From what has been stated hitherto it is obvious,—

1st. That the laws which govern the retardation of bodies gliding over each other are as the nature of those bodies.

2nd. That with fibrous substances, such as cloth, &c. friction is increased by surface and time, and diminished by pressure and velocity.

3rd. That with harder substances, such as woods, metals, and stones, and within the limits of abrasion, the amount of friction is as the pressure directly, without regard to surface, time, or velocity.

4th. That with dissimilar substances gliding against each other, the measure of friction will be determined by the limit of abrasion of the softer substance.

5th. That friction is greatest with soft, and least with hard substances.

6th. That the diminution of friction by unguents is as the nature of the unguents, without reference to the substances moving over them.

The very soft woods, stones, and metals, approximate to the laws which govern the fibrous substances.

In comparing the present experiments with those of COULOMB, the discordances found to exist relate principally to time. The limited pressures (varying from 1 to 45lbs. per square inch) under which his experiments were made, account in some degree for the anomaly. But in many of the minor, and in the general results, they will be found to coincide.

The subject might be illustrated still further by detailing the results of other experiments on the motions of machines, on the friction of solids revolving in fluids, and the descent of carriages down inclined planes. But as the present inquiry principally relates to the friction of attrition of solids, and as the experiments last mentioned have not been sufficiently matured to arrive at the necessary deductions, it only remains to conclude by expressing a hope, that the data now furnished will in some degree enlarge the bounds of our knowledge on this subject, interesting as one of philosophical inquiry, and intimately connected with every branch of the mechanical arts.