LABORATORY INVESTIGATION OF BRAKING CHARACTERISTICS OF CAST-IRON BRAKE SHOES USED BY RAILWAYS IN EUROPE

By

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1. Introduction

The Department of Railway Vehicles at Technical University, Budapest has long been dealing with laboratory testing of the frictional and wear properties of different cast iron materials for brake shoes [1].

As a following phase of this research work frictional and wear properties of cast iron brake shoes used by ten different European railway systems were examined.

From ten different brake shoes of original size, test specimens with a surface of 5 mm × 20 mm were processed. By using these test specimens, friction coefficients and wear have been measured at six different pressures ($p = 0.3; 0.6; 0.9; 1.2; 1.5; 2.0$ MPa) and at seven different constant speeds ($V = 20; 50; 100; 120; 140; 160; 200$ km/h).

Afterwards the measurement results were evaluated and, the brake shoes were classified according to the friction and wear characteristics.

2. The materials investigated, the test bench, the measuring procedure applied and the method of evaluation

The five basic elements in the chemical composition of the material of the ten brake shoes and the content of combined carbon are shown in Table I.

The five basic elements are as follows: total carbon (C), silicon (Si), manganese (Mn), phosphorus (P) and sulfur (S). Their percentage are indicated in the table.

From the textures of the materials in the original and changed states *photographs of polished metallographic specimens* have been made.

The most significant characteristics of the basic texture, i.e., the percentages of the ferrite F*, perlite P*, and steadit S* as well as the HB-hardness of the specimens processed from the brake shoes also are presented in the table.

Table 1

Composition %	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
C	3.20	3.20	3.23	3.04	3.20	3.36	3.23	3.36	3.04	3.00
C_k	0.93	0.85	1.09	0.77	1.09	0.97	1.26	1.29	0.77	0.91
Si	1.38	1.71	1.38	1.60	1.76	1.58	1.68	1.55	2.19	1.40
Mn	0.56	0.63	0.61	0.58	0.58	0.60	0.71	0.50	1.79	0.67
P	0.55	0.72	0.97	0.97	1.34	1.35	1.21	1.26	1.40	1.09
S	0.140	0.128	0.132	0.145	0.141	0.140	0.123	0.136	0.145	0.124
HB(5/750)	187	187	239	207	215	229	219	239	150	280
F*	0	3	0	25	0	1	10	0	0	0
P*	90	87	85	65	75	79	75	80	85	70
S*	10	10	15	10	25	20	15	20	15	30

F* = ferrite; P* = perlite; S* = steadit

The circuit diagram of the test bench and instruments are seen in Fig. 1. The engine (8) drove the disc (4) by means of the V-belt (9); the specimen (5) was pressed to the disc by a force F_t. The force F_t was controlled by weight loads. The friction force F between the specimen and wheel disc was measured electronically by a cell-dynamometer. The friction coefficient associated with the constant number of revolution (i.e., with the speed V) may be calculated from the friction force F and from the brake-shoe force F_t. The wear was determined by weighing the specimen before and after the braking test. The r.p.m. and the total number of revolutions were measured and summarized

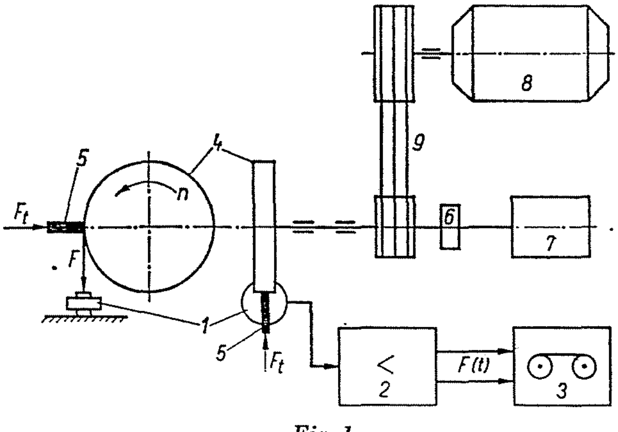

Fig. 1

behind the electronic tachometer (6) by the integrating counter of revolutions (7). This value was used for the calculation of the specific wear q.

The unit for the measurement of the force was a strain-gauge cell (1); the electric signal was amplified by the amplifier (2). The output signal was registered on a tape recorder (3). The electric signal of the friction force F contained a periodical component due to the oval form of the wheel, as well as a stochastic component due to the physical character of the friction process, and the disturbing oscillations developed at the test bench. For this reason, it seemed convenient to determine the average value of the electric signal. This is interpreted according to the formula:

$$\bar{F} = \frac{1}{T}\int_{0}^{T} F(t)\, dt$$

where

$F(t)$ function of friction force versus time
T period of integration.

The integration was performed with an analogue computer.

During the measurements, under the effect of the increasing load, first glowing spots appeared on the surface of the specimen and soon the whole surface began to glow in a depth of 1 to 2 mm and to slightly scintillate. This state of the specimen was judged to be acceptable. In case of a higher thermal load a strong scintillation started accompanied by a rapidly increasing wear and the value of the friction force began to strongly fluctuate in an irregular way. This state was considered unstable and was not evaluated in spite of the fact that there are situations where such strong wear and scintillation occur also under operational conditions.

For every pair of values four measurements have been performed. Here, it should be noted that the small-scale tests have not been carried out in every respect according to the model corresponding to the laws of the similarity merely the geometric similarity of the frictioning surfaces has been assured, so that the numerical results are not directly valid under actual conditions; they are only suitable for the qualitative evaluation of the materials investigated. It is a general experience [2] that in case of identical surface pression and speed, with the decrease of the frictioning surface the value of the friction coefficient increases. In this connection the instance in question represents an extreme case because the specimen with its surface of 1 cm^2 practically is of zero extent. This explains the extraordinary high friction coefficient values obtained. In addition to the high friction coefficients the measurement results are featured by the fact that the friction power which the materials can endure even without a significant wear increase and strong scintillation, is significantly higher than the values occurring in service.

The reason for this is that the model does not simulate the real thermal conditions. In case of a brake shoe of actual size, the ratio of heat emitting

Table 2

V	p	F	μ	q	P
20	0.3	21.6	0.72	2.2	0.12
	0.6	37.2	0.62	14.2	0.21
	0.9	52.2	0.58	19.5	0.32
	1.2	66.1	0.55	28.8	0.37
	1.5	79.7	0.53	37.6	0.44
	2.0	102.0	0.51	55.3	0.57
50	0.3	17.1	0.57	5.9	0.24
	0.6	29.5	0.49	24.8	0.41
	0.9	42.3	0.47	35.1	0.59
	1.2	54.0	0.45	47.2	0.75
	1.5	64.4	0.43	65.2	0.90
	2.0	83.8	0.42	82.5	1.16
100	0.3	13.8	0.46	4.4	0.38
	0.6	23.8	0.40	18.6	0.66
	0.9	34.1	0.38	34.3	0.95
	1.2	43.1	0.36	47.4	1.20
	1.5	52.4	0.35	54.9	1.48
	2.0	67.5	0.34	66.4	1.88
120	0.3	13.1	0.44	9.6	0.44
	0.6	21.6	0.36	26.5	0.72
	0.9	30.6	0.34	33.0	1.02
	1.2	38.4	0.32	40.3	1.28
	1.5	47.3	0.31	62.7	1.58
	2.0	62.0	0.31	70.8	2.07
140	0.3	12.2	0.41	4.5	0.47
	0.6	20.7	0.34	20.3	0.80
	0.9	28.8	0.32	32.0	1.12
	1.2	37.2	0.31	39.8	1.45
	1.5	45.3	0.30	47.2	1.76
	2.0	—	—	—	-
160	0.3	12.0	0.40	11.1	0.53
	0.6	21.3	0.35	31.0	0.95
	0.9	28.8	0.32	38.7	1.28
	1.2	37.2	0.31	49.3	1.65
	1.5	45.4	0.30	59.7	2.02
	2.0	—	—	—	—
200	0.3	11.1	0.37	8.8	0.62
	0.6	22.1	0.37	23.9	1.23
	0.9	33.3	0.37	39.8	1.85
	1.2	46.1	0.38	57.5	2.56
	1.5	57.2	0.38	84.7	3.18
	2.0	—	—	—	—

to heat absorbing surface of the brake shoe is only 1.6 to 1.8, while in case of the model tests this value amounts to 15 to 16. This and numerous other circumstances, as for example, the difference between the ways of clamping, all present effects which increase the thermal capacity and the load capacity of the specimen in laboratory model tests, i.e., permit the transfer of higher braking power.

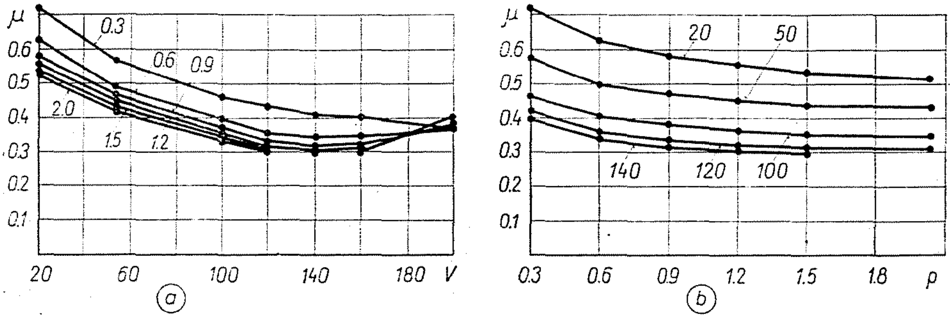

Fig. 1

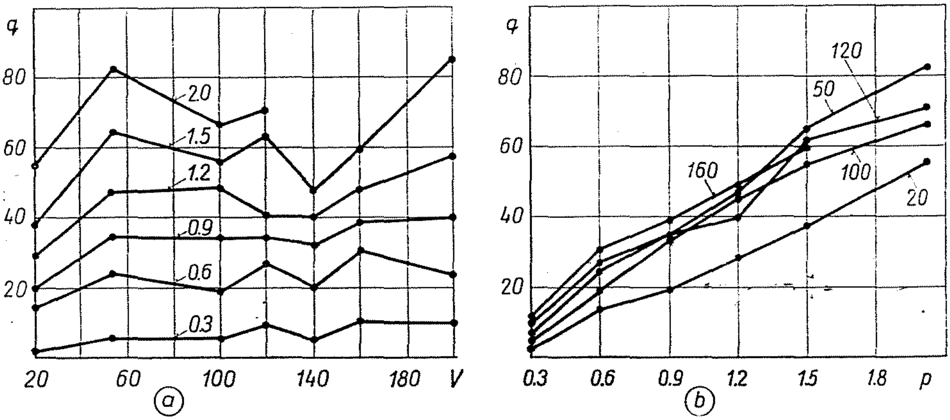

Fig. 2

The measurement results as well as their processing method are shown in Table II. Material N° 7 was chosen as an illustrative example. In this table, the friction force F(N) measured at the given speed V (km/h) and at a pressure p (MPa), the friction coefficient μ calculated from them the specific wear q (mg/km), as well as the friction power $P = FV$ (kW) are indicated.

Several diagrams may be plotted on the basis of the tabulated data which clearly demonstrate the braking characteristics of the materials. Thus, for example, for the material N° 7 the diagrams $\mu = f(p, V)$ and $q = f(p, V)$ are seen in Figs 2 and 3, respectively.

In this connection it is to be noted that the braking behaviour of the materials, i.e., whether the brake shoe material in question meets or does not meet the requirements, cannot be decided on the basis of a single index number. In general one can say that the brake shoe material is satisfactory if it meets at least three of the requirements, such as:

1. an appropriate friction coefficient which only little depending on the speed and pressure;

2. a favourable load capacity (in this respect, the product $P = FV$ is characteristic);

3. a low wear value.

However, beside these ones other, in special cases significant properties must not be neglected such as, with materials of lower phosphorus content the proneness to burring and breaking up, while in case of materials of higher phosphorus content the phenomenon of violent scintillation, the reliable low-standard-deviation value of the friction coefficient.

In the following, the evaluation of the braking behaviour of the different materials has been performed on the basis of the above considerations.

3. Estimation of the friction characteristics

The estimation of the frictional behaviour of the different materials is encumbered by the fact that there is no friction coefficient which could be considered theoretically to be the best one; the friction coefficients obtained for the different materials should be valuated both in themselves and with respect to each other. As noted above, in judging the friction conditions the homogeneity of the friction coefficients is of importance, i.e., it is favourable if the friction coefficients do not much vary versus the parameters p_i and V_j. Marking the rows and columns of a matrix by test pressures p_i and speeds V_j the frictional behaviour of the different materials can be described by matrix analysis.

Let us now consider the friction coefficients at point (p_i, V_j) as the elements of a matrix. At those points where the material could not support the load, the element has a value of zero. It is obvious that the material is the better where the number of zeros in the matrix is lower. Another index is the sum of the matrix-elements which may be designated as the norm of the matrix, due to the fact that the matrix in question has no negative elements. The numerical value of the norm is high if the values of the friction coefficients are, in general, high and in addition they vary little and the number of zero elements is low. All opposite effects decrease the value of the norm. In Table III, the matrix norm values $\sum_{i=1}^{6} \sum_{j=1}^{7} \mu_{ij}$ have been assembled for ten different materials.

Table 3

$P_{[MPa]}$	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
	$\Sigma\mu_j$									
0.3	3.23	3.39	3.27	3.07	3.25	3.16	3.37	3.07	3.41	3.16
0.6	2.88	3.06	2.97	2.81	2.89	2.95	2.93	2.88	3.00	2.85
0.9	2.72	2.85	2.78	2.65	2.68	2.68	2.78	2.68	2.81	2.66
1.2	2.58	2.72	2.66	2.56	2.50	2.50	2.68	2.37	2.65	2.53
1.5	2.50	2.62	2.58	2.09	2.05	2.06	2.60	2.15	1.78	2.10
2.0	1.18	1.15	1.47	1.44	1.35	1.40	1.58	1.47	1.41	1.71
$\Sigma\Sigma\mu_{ij}$	15.09	15.79	15.73	14.62	14.72	14.75	15.94	14.82	15.06	15.01
Sequence	4	2	3	10	9	8	1	7	5	6
$P^{[kW]}_{max}$	3.08	3.28	3.00	2.41	2.07	2.33	3.18	2.21	2.50	2.14
Sequence	3	1	4	6	10	7	2	8	5	9
$\Sigma\overline{N}$	38	38	39	38	38	38	39	38	37	39

However, the difference between these materials is not significant because for example, the quotient of the norm characteristics of the poorest material N° 4 by the best material N° 7 is only 0.92.

On the basis of the numerical results obtained, a certain hierarchy of valuation may be established.

In a row of the table also the highest values of the braking power P_{max}, as well as the number of the non-zero elements ΣN of the matrices associated with each material have been presented.

In conclusion it may be stated that the material N° 7 showed the best behaviour while the second-best was N° 2.

4. Estimation of the wear behaviour

The wear resistances of the materials investigated significantly differ from each other, however, certain tendencies may be established.

Thus, for example, the specific wear depends, first of all, on the surface pressure, and only in a small degree on the speed. The low effect of the speed is, in all probability, the consequence of that the heat produced by braking affects the mechanical and metallographic state of the material.

In examining the wear diagrams it seems to be remarkable that about the speed $V = 50$ km/h and in the case of high p-values the specific wear is, in general, rather strong.

It is also evident that the value of the specific wear increases with the force F and load p. The materials cannot carry certain high loads and the rapid wear accompanied by violent scintillation escapes measurement.

In final account the wear behaviour of the different materials has been analyzed by averaging wear values $\bar{q}$ for each material (assuming p = const.). The results of the calculation are listed in Table IV. The mean of the average wears ($\bar{\bar{q}}$) are presented in the lowest but one row of the table. By investigating these entries one can observe that materials differ by much more than in the case of the friction coefficients. Thus, for example, the quotient of the mean values of wear $\bar{\bar{q}}$ of the material N° 7 with very favourable frictional and load bearing properties by the weakest material N° 1 is equal to 0.66.

Table 4

P[MPa]	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
	$\bar{q}$ [mg/km]									
0.3	7.7	9.4	10.0	9.4	9.0	9.0	6.6	8.9	7.7	9.3
0.6	27.7	23.8	24.9	23.3	25.7	26.7	22.8	26.9	22.2	22.9
0.9	43.7	37.1	39.3	38.6	38.9	37.4	33.2	31.2	35.0	36.4
1.2	59.1	48.7	53.4	53.5	53.5	50.6	44.3	55.0	48.9	49.2
1.5	80.1	62.2	68.7	68.7	59.5	61.6	58.9	64.4	50.2	59.5
2.0	135.3	88.8	91.2	84.1	80.3	82.4	68.8	80.8	58.3	74.8
$\bar{\bar{q}}$[mg/km]	58.9	45.0	47.9	46.3	44.5	44.6	39.1	46.2	37.1	42.0
Sequence	10	6	9	8	4	5	2	7	1	3

5. The method of mathematical statistics suitable for the valuation of the test results and their evaluation

The frictional and wear characteristics of the brake-shoe materials may be determined also by the method of mathematical statistics. To be short, only the methods of estimating the friction coefficient will be dealt with, however, fully analogous statements may be made on wear.

At a given point (p_i, V_i) the corrected empirical standard deviation $S^*(p_i, V_i)$ of sample values $\mu(p_i, V_i)$ originating from a random field $\mu(p, V)$

in case of a sample of N elements may be calculated by the relationship [3]:

$$S^*(p_i, V_i) = \sqrt{\frac{\sum_{j=1}^{N} [\mu_j(p_i, V_i) - \bar{\mu}(p_i, V_i)]^2}{N-1}} .$$

The empirical relative standard deviation of the sample of N elements may be determined at every point (p_i, V_i) by using the formula

$$\sigma_r(p_i, V_i) = \frac{S^*(p_i, V_i)}{\bar{\mu}(p_i, V_i)} .$$

With the knowledge of the phenomenon, the relative empirical standard deviations associated with the points (p_i, V_i) can be assumed of approximately identic distribution, therefore, the mean value of the relative standard deviations at all of the points also may be established:

$$\bar{\sigma}_r = \frac{\sum_{i=1}^{M} \sigma_r(p_i, V_i)}{M}$$

wherein M is the number of all of the points (p_i, V_i). So, all information carried by the measurement results have been utilized.

By considering the empirical relative standard deviation $\sigma_r(p_i, V_i)$ associated with each point (p_i, V_i) as random variables having approximately identical distribution functions, from the actually measured realization values the average $\bar{\sigma}_r$ of the empirical relative standard deviation $\sigma_r(p_i, V_i)$ as well as its corrected empirical standard deviation $S^*(\sigma_r)$ may be calculated. Consequently, for a given grade of material, the low value of $\bar{\sigma}_r$ refers to a slight scatter in the random field about the function of the expected values; the low value of $S^*(\sigma_r)$ designates that the relative standard deviation only little depends on the choice of point (p_i, V_i). From what is said above ensues that those materials are appropriate for which the elements of the pair $\bar{\sigma}_r$ and $S^*(\sigma_r)$ are small. Thus, by calculating the actual values with the use of both $\bar{\sigma}_r$ and $S^*(\sigma_r)$ a quality sequence may be established.

The materials may also be characterized in a similar way by the product of these two elements, in fact, the product $R = \bar{\sigma}_r . S^*(\sigma_r)$ bears both effects. For the sake of completeness also this product has been calculated.

Arranging the different materials in series according to the standard deviations of the two properties — friction and wear — and forming the algebraic sum of the serial numbers, so the materials with favourable standard deviation rated lower, while those of less favourable one are rated higher.

According to this way of qualification, good materials are N° 7 and N° 2 while N° 4 and N° 6 being rather poor.

However, it should be noted at all events, that the above considerations relating to the mean values of the friction coefficients and wear give only partial information in connection with the rating of the materials; they only permit a proper classification together with the information presented in the foregoing.

Table 5

Material / Classification according to	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
$\Sigma\mu_{ij}$	4	2	3	10	9	8	1	7	5	6
P_{max}	3	1	4	6	10	7	2	8	5	9
$\bar{\bar{q}}$	10	6	9	8	4	5	2	7	1	3
R_μ	5	4	9	7	6	10	3	1	8	2
R_q	4	3	5	10	8	9	1	7	2	6
Overall sequence	5	2	6	10	8	9	1	7	3	4

In Table V, the results of the sequences established on the basis of different viewpoints are summarized. By forming the algebraic sum of sequences, a sequence bearing all information might be established. By this way the two best materials turned out to be N° 7 and N° 2 while N° 4 and N° 6 were the poorest ones.

Evidently, by weighing the sequence according to different characteristics from braking aspects the rating and the final order might further be refined.

6. Concluding remarks and suggestions

a) From all aspects of comparison material N° 7 gave the best results but little superseding material N° 2.

b) The fact known from the practice [1] that the increase of the phosphorus content very significantly grades up the frictional behaviour of the cast-iron brake-shoe materials was not experienced in small-scale tests. Thus, for example, the rather favourable frictional behaviour of the low-phosphorus material N° 2. So, it should be subjected to a more detailed and more thorough investigation in order to find out which the factors are that engender these favourable properties.

c) The results of the wear tests definitely evidenced that the increase of phosphorus content favourably affected the wear conditions.

d) In case of cast-iron brake-shoes the brakeshoe pressure cannot infinitely be increased because, beyond a certain limit load, beside the wear accompanied by strong scintillation also the other friction properties become unstable.

e) For a deepgoing investigation of stochastic laws of frictional processes, further measurements series are necessary which more exactly reveal the standard deviation of the random field $\mu(p, V)$. For this purpose, about 30 independent measurements are needed at every point (p_i, V_i).

Summary

In our days, unification of cast-iron brake-shoe materials used by European railway systems forms an important field of the research work. As one phase of this research work, the frictional and wear properties of cast-iron brake-shoe materials used by ten different European railway systems have been investigated in laboratory tests. In this paper the measurement and evaluation methods are presented and, on the basis of the results obtained, the different brake-shoe materials are rated.

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