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# INVESTIGATIONS ON THE SELECTION OF FRICTION MATERIALS DESTINED TO RAILWAY VEHICLES APPLICATIONS

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**ABSTRACT**: The main factor that influences the selection of a friction material for railway applications is the performance criterion (friction and wear). This criterion differs from one market to another and may be defined by local operators or by organizations, which set international standards. The choice of friction material can have a direct influence on the wear life of the brake block or wheel, which is typically much more expensive to replace. The classical cast iron brake block is gradually replaced by organic composite or sintered composite brake blocks. Nowadays is devoted attention to solving problems connected with using modern brake materials and its impact on thermal and mechanical loading of railway wheels. In this work the investigated subjects are the gray cast iron brake shoes, with lamellar graphite and with a high content of phosphorus (0.8–1.1%), according to requirements for the brake shoes related materials.
**Keywords**: brake shoes, gray cast iron, phosphorus, quality assurance, correlation diagrams

## 1. INTRODUCTORY NOTES

The railway's history over the last 50 years, and especially the last 20 years, has been punctuated by major technological changes. The leap in the popularity of high–speed trains played a key role in this evolution, which is both irreversible and fundamental to passenger and freight transport.[1,14] In the past 20 years, rapid developments in the railway industry have been accompanied by increases of speed, loads, and engine power.[2,14] The friction materials used in the railway industry are required to provide a stable friction coefficient and a low wear rate at various operating conditions (like speeds, pressures, temperatures), and environmental conditions (noise, constant performing in extreme weather). All of these requirements need to be achieved at a reasonable cost.[2,14]

To encourage train transport, the tendencies of trains do not focus just on delivering the right comfort for passengers, but also on increasing traffic speed, together with the high level of safety, less costs and increased availability. These are the main challenges as regards braking systems. [3] The technological development has permitted these elements, although they are the most exposed equipments of a rail vehicle, to optimize the transport safety level and to act rapidly and efficiently in case of emergencies.[3,14,15]

Train braking is a very complex process, specific to rail vehicles and of great importance by the essential contribution on the safety of the traffic. This complexity results from the fact that during braking occur numerous phenomena of different kinds – mechanical, thermal, pneumatic, electrical etc. The actions of these processes take place in various points of the vehicles and act on different parts of the train, with varying intensities. The major problem is that all must favorably interact for the intended scope, to provide efficient, correct and safe braking actions. Friction products are safety–critical items, which must be carefully designed and selected to ensure several performance criteria. The design or formulation selected is a compromise between several conflicting priorities and the trade–offs can be tailored according to the wide range of different customer requirements that exist in the market. [2,14] Three principal factors influence the selection of a friction material for railway applications, which are:

- ≡ performance (control of friction and wear, braking efficiency and uniform dissipation of heat, operating temperatures, control of vibration and impact),
- ≡ environmental considerations (reduction of noise, constant performance even in the most diverse weather and operating conditions), and
- ≡ cost (overall life–cycle cost, life cycle costs per wagon, brake block cost, operating cost, labor cost of replacement, cost for brake block disposal, prices).

The product must also fulfil specific frictional performance criteria over a range of speeds and braking efforts. These criteria differ from one market to another and may be defined by local operators or by organizations, which set international standards. [2,14] Because of the complexity of railway operations, many operators will already have management systems and processes in place to handle other requirements such as safety validation. In many cases, safety and environmental issues go hand in hand, so it may well be an advantage to integrate an environmental policy into other management systems. The pressure to reduce costs in the rail industry often means that brake shoes are viewed as commodity items, often replaced on a lowest price basis providing the performance is satisfactory. Few realize this may not produce the lowest operating cost: the choice of friction material can have a direct influence on the wear life of the wheel, which is typically much more expensive to replace.[2,14] In other studies, relating to block and shoe materials, a similar outcome has been observed. For these applications, the rate of wheel wear is the factor, which determines the overall life–cycle cost, rather than simply the cost of the block itself. [2,14]

The progress that has been registered in the railway techniques and especially in the modern railway traction, have allowed a continuous increase of speed and loading, the braking system etc. But, at the same time, a series of difficult tribological and complex problems are required to be resolved.[3,4,13–15] Thus, problems related to the wear of these railway components are actually, and in this sense, tribological concerns is heading and toward obtaining and using certain materials with good friction and wear qualities. The technological concerns goes both to the study of wear of the steel wheel, given the mechanical and thermal complex efforts to which they are subject, but also to the related problem of the brake shoe–wheel system. [2,14]

An essential ingredient in the successful running of a railway is a well–maintained system and in a modern railway system the wear on rails, braking shoes and wheels causes high maintenance costs. In addition, non–uniform wear of rail or wheel may lead to undesirable vibrations and noise. Although the most exposed element in case of collision, vibrations and extreme weather conditions, the continuous development of this braking system permits the increase of the vehicle's speed in maximum safety conditions.[3,4,14,15]

The brake systems producers constantly carry out comparative and comprehensive tests, quality control tests, assessments, research and development of solutions aimed at obtaining the best results in terms of environmental compatibility and maximum performance efficiency. [3–5,15]

Braking the railway vehicles has developed with the increase in tonnage and the speeds of the circulation of the trains. Given the importance of braking in the railway transport the results of theoretical and experimental research is not entered in the practice until after a long testing and verification process.

## 2. BRAKE FRICTION MATERIALS

The braking system is one of the most important and complex subsystems of railway vehicles, especially when it comes for safety. Rolling stock is the most maintenance intensive part of the railway system and is the most vulnerable if maintenance is neglected. Therefore, installing efficient safe brakes is essential. Currently, the market of braking systems suppliers is extremely varied and this is shown in the design and manufacturing of the braking systems up to testing, validation and maintenance procedures. The passengers' demands launch challenges for manufacturers in the development and design of complex and

Figure 1. Several grades of wear on the wheel

compact braking systems matching safety and flexibility with high performance. [3,4,5] The friction materials have been developed by the producers keeping the qualification in these fields:

≡ safety in exploitation,
≡ performance and durability,
≡ environmental impact.

Brake friction materials play an important role in braking system. [3–5,6] During a braking process, brake shoes are pressed against the rotating wheel. During this process, the friction materials and the brake shoes are subjected to wear (Figure 1 and Figure 2). Characteristic of friction materials is very complex to predict and it is a critical factor in brake system design and performance, but advances in braking technology are generating substantial savings in operating costs while helping to reduce the environmental impact of trains.

To achieve ideal brake friction material characteristics, such as constant coefficient of friction under various operating conditions, resistance to heat, water and oil fade, low wear rate, possess durability, heat stability, exhibits low noise, and not to damage brake shoes, some requirements have to be compromised in order to achieve some other requirements. [2,4] Consequently, the braking system producers must guarantee:

≡ stable and reliable coefficients of friction;
≡ control of the brake fading effect (coefficient of friction reduction);
≡ braking efficiency and uniform dissipation of heat developed when applying the brakes;
≡ great match performance–use;
≡ reduction of noise, in all the operating conditions, thanks to the perfect balance of the chemical/physical properties of the compound components.

However, it is practically impossible to have all these desired properties. Designers have extensive freedom in dimensioning brakes for new vehicles and it is not always necessary to reproduce the friction coefficient of the cast iron brake shoe. The only essential requirement is that equivalent speeds produce equivalent stopping distances. [6,7,8,13,14] Therefore, some requirements have to be compromised in order to achieve some other requirements. In general, each formulation of friction material has its own unique frictional behaviors and wear–resistance characteristics. [6,7,8,14]

The interaction between the cast iron brake block and the steel wheel produce complex thermos–mechanical phenomena. Therefore, tread braking with cast iron blocks rapidly leads to high wheel roughness. Cast–iron brake shoes, still widely used on freight wagons, make the wheel surface much rougher than a similar product made from composite material due to the fusing of minute metal particles into the tread surface during braking (Figure 2). Different researches suggest that composite brake blocks would lead to higher wheel wear (in comparison with cast iron blocks) but would show lower block wear in similar operating conditions. The lifetime of the wheel depends on:

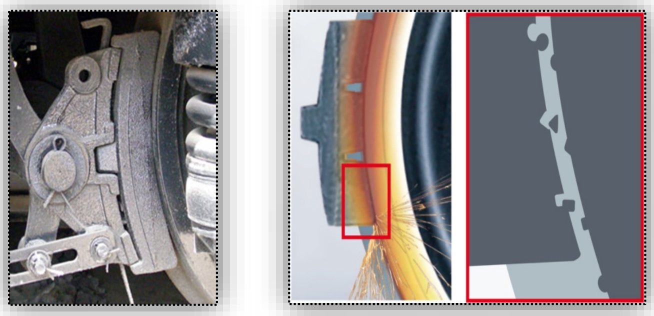

Figure 2. The brake shoes subjected to wear on wheel

≡ different brake block solutions used that cause different wheel wear;
≡ rejection of running surface and wheel defects (wheel flats, cracks, wear etc.) that cause wheel re–profiling;

Along the time, for railway vehicles have been developed various brake systems, whose construction, design and operation depend on many factors such as running speed, axle load, type, construction and technical characteristics of vehicles, traffic conditions, etc. Among various principles and constructive solutions that were developed, following the studies and especially the results of numerous tests, the indirect compressed air brake system proved to have the most important advantages. Therefore, it was generalized and remains even nowadays the basic and compulsory system for rail vehicles. [4]

The brake system covers all equipment and devices fitted on the railway rolling stock within scope of reducing the speed or stop the train. The types of braking systems used in the present on the rolling stock at the majority of the railway administrations may be classified according to several criteria. However, the most used is the braking with friction shoes, at which the friction achieves the braking force produced between the gray iron shoes and the steel wheels running surface.

Brake shoe is the most used at the rolling stock. The wheel is requested, on the one hand, by the forces necessary for the conduct of the rail vehicle, and, on the other side, by the braking forces. For the second category of request, it is necessary to establish the limits of temperature and wear.

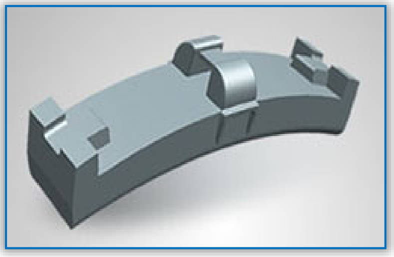

Figure 3. Brake shoe

Figure 4. Brake head

Brake blocks, also called "shoes", are made of cast iron, respecting the principle of having a different hardness (and resulting wear) from the other elements of the friction pair, i.e. the wheel (made of steel). Cast iron blocks have specific features, like a rather high weight, limited cost, easy supply and a peculiar friction coefficient dependency on the sliding (vehicle) speed. [6–10] As coefficient of friction decreases with speed, the braking system of tread–braked vehicles has been designed to exploit the capabilities of such material at the best.

Development and certification of a friction material is a complex, time–consuming and expensive process, especially when field trials are necessary to verify the material's performance over an extended period. Dependent on the industry structure and the relationships between train operators and maintenance contractors, full information regarding train use, material performance and service intervals may not be readily available to the friction material supplier. In these circumstances, the most effective route to the development of materials that offer improved life–cycle costs is for the supplier to work in partnership with one or more of the parties involved so that the key targets can be built in at an early stage of the material development programs.

Brake shoes are made in a variety of materials (cast iron, composite, sintered), all of which have their own drawbacks (hard on the wheels, a low friction coefficient, cost etc.). [9,11,12] Traditionally, freight wagons were fitted with brake systems using cast iron blocks. Passenger wagons still resist and are nowadays equipped with the original solution of cast iron brake blocks. The main disadvantage of cast iron is the double dependency of its friction coefficient versus speed and application force. Nevertheless, it has to be admitted that cast iron brake shoes offer a number of advantages, including:

≡ their friction coefficient is almost independent from atmospheric conditions;
≡ the material properties are independent from the manufacturer;
≡ they guarantee a suitable dissipation of heat generated during braking;
≡ small flats are grinded–down during subsequent brake applications;
≡ due to the constant roughening of the wheel surface a consistent adhesion level is maintained.

The totally replacement of a standard and well–known material (cast iron) with a completely different one (composite blocks) has not been made. Although the composite brake blocks were considered as reliable enough for the general use in railway transport, several types of block requires a modification to the vehicle braking system. In the last few decades, the use of sintered or synthetic materials has become common in the railway industry, and in different proportions depending on the vehicle and on the application. [11,12]

## 3. PHOSPHOROUS CAST IRONS FOR BRAKE SHOES MANUFACTURING

On manufacturing brake shoes meant for the rolling stock, phosphorous cast irons are largely used. Their friction coefficient diminishing dramatically on braking at the relative high speeds (up to 120–140 km/h), while their wear is growing when the temperature in the braking coupling goes up. Therefore, their use as simply cast irons is limited for railway vehicles running at speeds of up to 120 km/h.

For making brake shoes are used frequently gray cast iron with lamellar graphite and nodular cast iron, which have a good thermal conductivity (necessary for the proper discharge of heat due to friction), good mechanical properties, good wear resistance. The main elements of its chemical composition in Table 1 are presented and mechanical properties fall within the intervals corresponding to the desired purpose. Cast iron brake block enjoys many advantages including hardness, impact strength and so on. It consists of two parts, the cast iron and the steel support.

Both the surface and core of the cast iron have the hardness within the range of 197< HB< 225. [10,13–15]

Table 1. Chemical compositions of cast iron and steel support

| Chemical compositions of cast iron | | Chemical compositions of steel support | |
|---|---|---|---|
| Main components | Proportion, [%] | Components | Proportion, [%] |
| Carbon, [C] | 3.0–3.5 | Carbon, [C] | < 0.13 |
| Phosphorus, [P] | 1.3–1.5 | Sulphur, [S] | < 0.062 |
| Silicon, [Si] | 1.5–2.0 | Phosphorus, [P] | < 0.062 |
| Sulphur, [S] | 0.1–0.15 | | |
| Manganese, [Mn] | 0.5–0.8 | | |

It has been demonstrated that, in the railway breaking system, the shoe's iron graphite, respectively the wheels steel's chromium, are the most helpful structural elements in the materials intended to friction. As regards the graphite form are talking yet whether it is preferable (globular or lamellar), but it is known that the carbon content must represent approx. 3.2 % in the final chemical composition of these irons.

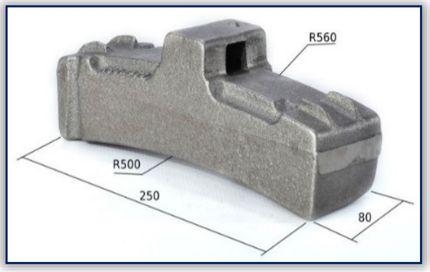


Figure 5. Gray cast iron brake shoes for passenger trains

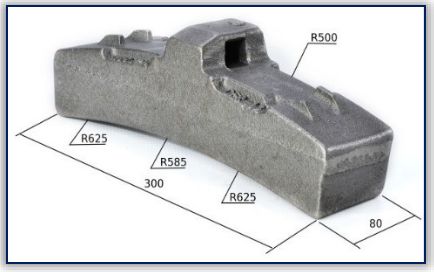


Figure 6. Gray cast iron brake shoes for freight wagons

A common characteristic constituent of gray iron microstructures is the phosphorus ternary eutectic known as steadite ($Fe_3C$ + $Fe_3P$ + P). The characteristic property of this system is a large area of the ternary phosphorous eutectic due to the strong tendency for phosphorus to segregate. The form of the phosphorus eutectic depends on the chemical composition of the gray iron. In irons with an average tendency to graphitization and a phosphorus content of approximately 0.4%. The microstructure of each cast iron destined to the brake shoes was composed of steadite, cementite and flaky graphite distributed in pearlitic matrix. The high content of phosphorous improves the friction – wear behavior of such cast iron

The structural changes occurring under the action of the phosphorus content, able to influence the properties of the cast irons are on the increase of the quantity of graphite and finishing it, the increase in the quantity of phosphorous eutectic and its distribution in the network form and obtaining the more quantity of perlite. Increasing the resistance is favored as long as the phosphorous eutectic is disposed in the form of isolated separation. Also, due to the increase of the perlite's proportion and especially of the phosphorous eutectic, as high hardness constituent (500–600 HB), by the addition of phosphorus the general hardness is increased.

## 4. STATISTICAL EXPERIMENTS

One of the main chapters of the statistics referring to the ability to predict. Although it is not find the perfect relations, by means of regression, can make statements of a variable, depending on the other values. The present researches are going to establish the influence of the chemical elements in the structure upon the mechanical properties (hardness) of the braking shoe material (gray phosphorous cast iron with lamellar graphite). The technological manufacturing process of the brake shoes, as well as the quality of material used in manufacturing them, can have a different influence upon the quality and the safety in the exploitation.

A major feature with huge impact on sustainability in the brake shoe is the hardness. At the brake shoes, hardness shall be determined in five points, two located at the ends of the shaker (on the same front side section) and three in section of the shaker (diagonal cross–section). [13] Our proposal approaches the issue of quality assurance of the brake shoes, from the viewpoint of the quality of materials, which feature can cause duration and safety in exploitation. In order to achieve the chemical composition behavior upon the shoe's hardness 100 charges were analyzed. A few interpretations of the correlations between the cast irons chemical components – Carbon (C), Silicon (Si), Manganese (Mn), Phosphorus (P) and Sulfur (S) – and the obtained brake shoes hardness (HB) was enounced. We propose three (3) kinds of correlations, using the Matlab area.

In the first experiment, we analyze the general behavior of Carbon content in relation with the rest of chemical elements, which have influence on the hardness of brake shoes. As result, regression surfaces and correlation diagrams are revealed, presented in the figures 7–14.

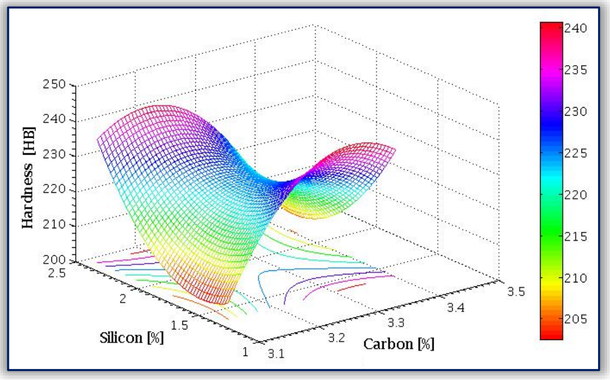


Figure 7. Regression surface, case of HB=f(C,Si)

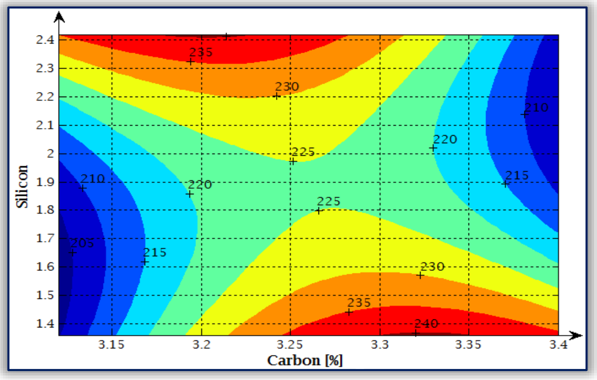


Figure 8. Correlation diagram, case of HB=f(C,Si)

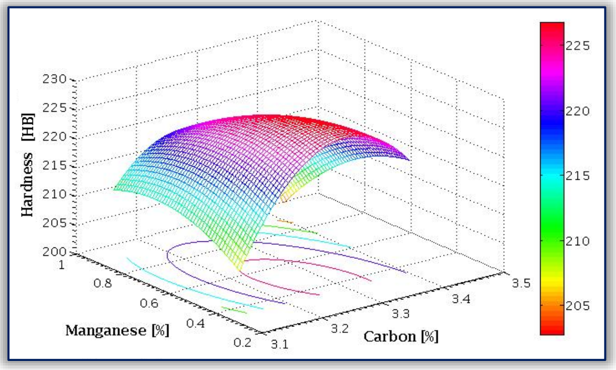


Figure 9. Regression surface, case of HB=f(C,Mn)

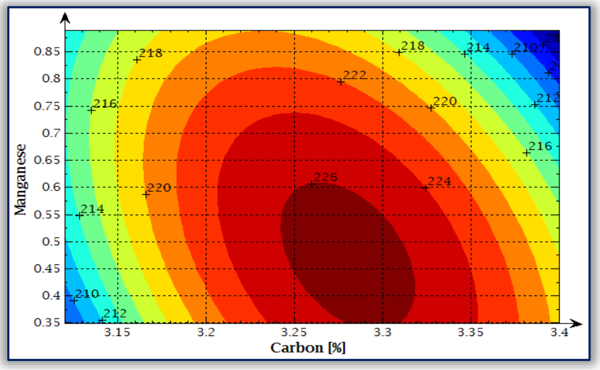


Figure 10. Correlation diagram, case of HB=f(C,Mn)

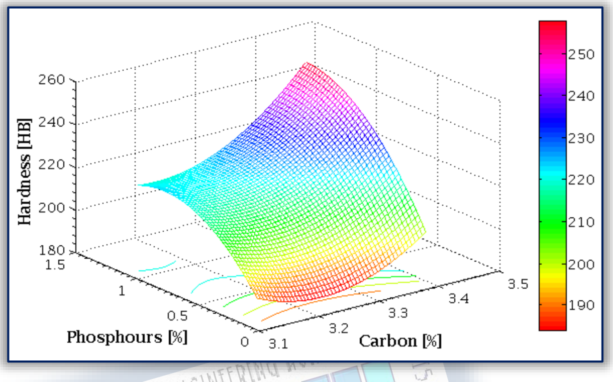


Figure 11. Regression surface, case of HB=f(C,P)

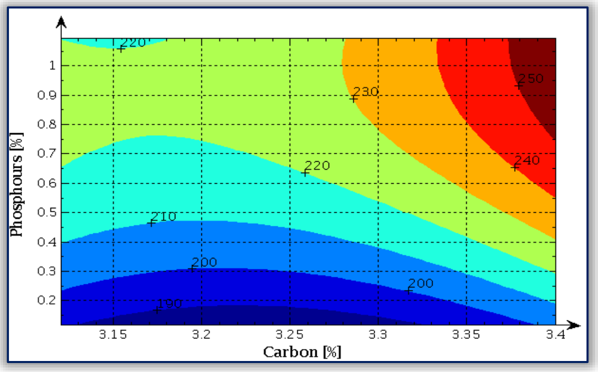


Figure 12. Correlation diagram, case of HB=f(C,P)

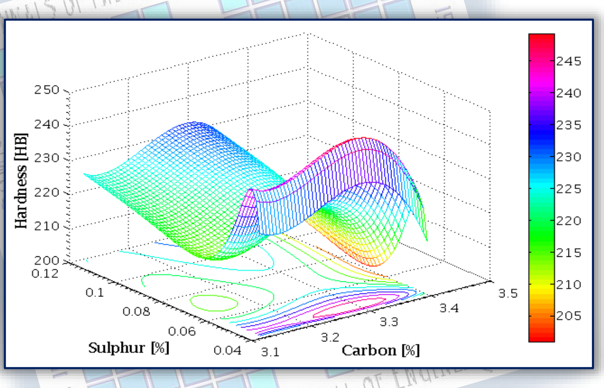


Figure 13. Regression surface, case of HB=f(C,S)

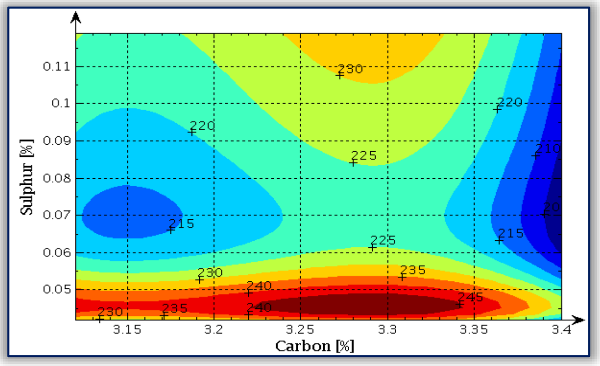


Figure 14. Correlation diagram, case of HB=f(C,S)

As second statistical experiment, followed by the Matlab graphic area representations, we analyzed the combined behavior of all chemical elements of gray phosphorus cast iron on the hardness of brake shoes, in several correlations. As result, regression surfaces and correlation diagrams are revealed, presented in the figures 15–24.

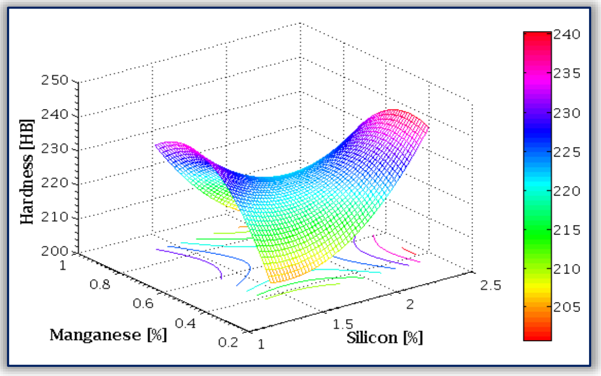


Figure 15. Regression surface, case of HB=f(Mn,Si)

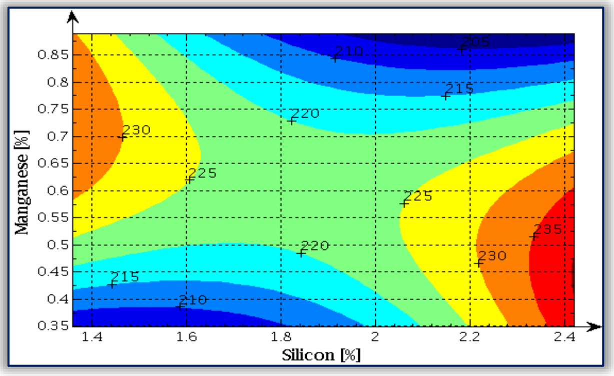


Figure 16. Correlation diagram, case of HB=f(Mn,Si)

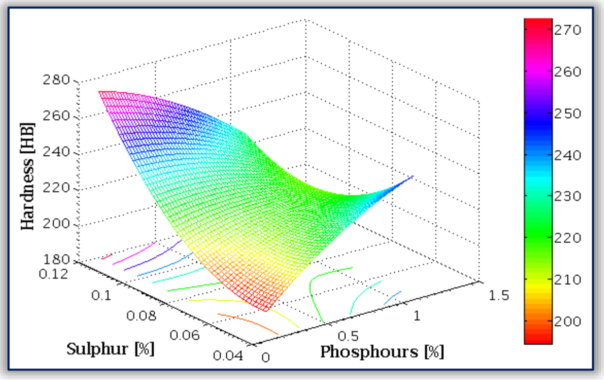


Figure 17. Regression surface, case of HB=f(P,S)

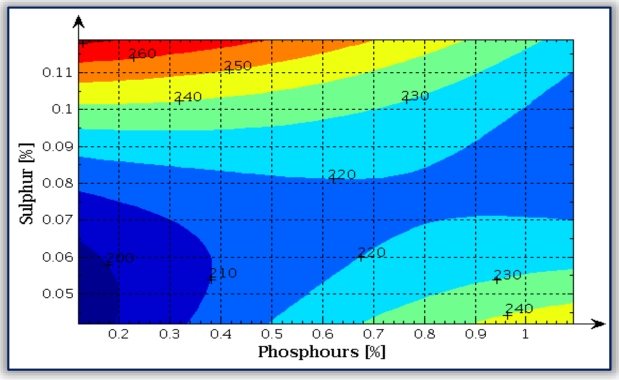


Figure 18. Correlation diagram, case of HB=f(P,S)

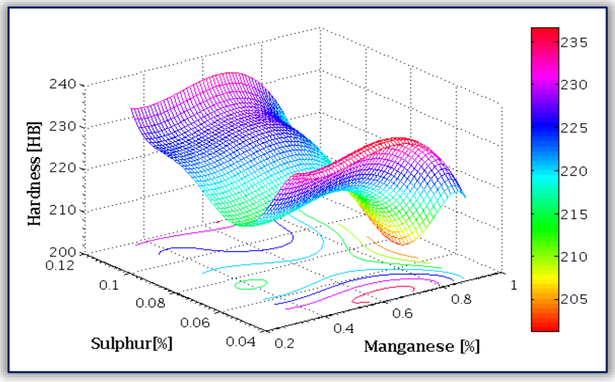


Figure 19. Regression surface, case of HB=f(Mn,S)

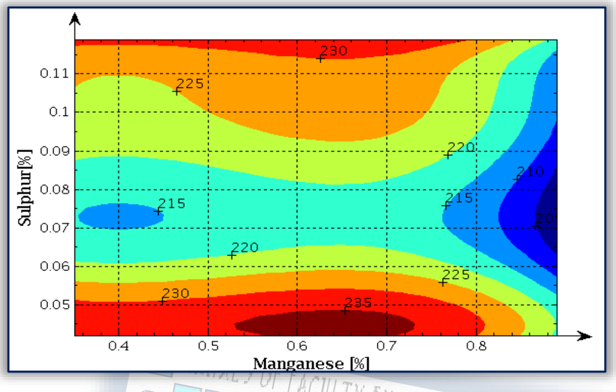


Figure 20. Correlation diagram, case of HB=f(Mn,S)

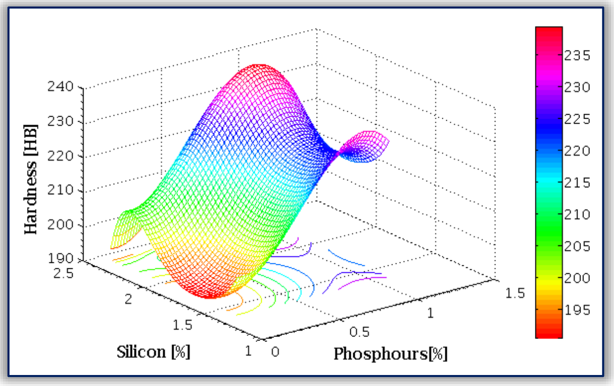


Figure 21. Regression surface, case of HB=f(Si,P)

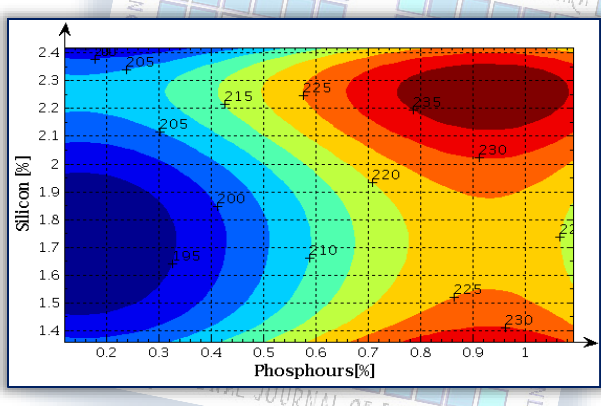


Figure 22. Correlation diagram, case of HB=f(Si,P)

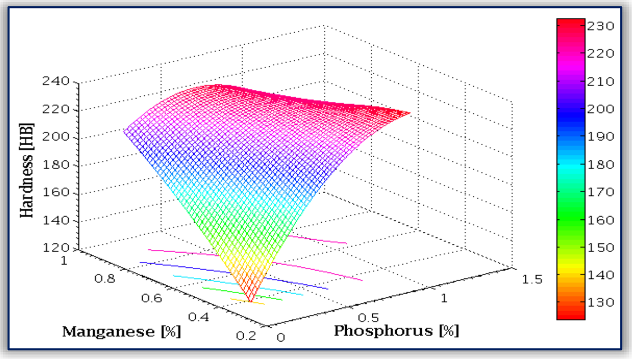


Figure 23. The regression surface, case of HB=f(Mn,P)

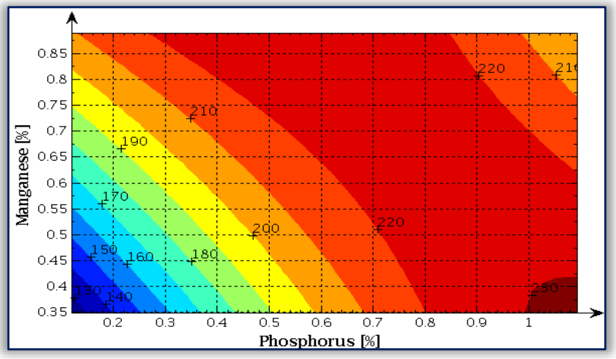


Figure 24. Correlation diagram, case of HB=f(Mn,P)

As third experiment, we analyze the equivalent carbon content value behavior on the hardness of cast iron brake shoes. As result, several regression surfaces and correlation diagrams are revealed, presented in the figures 25–26.

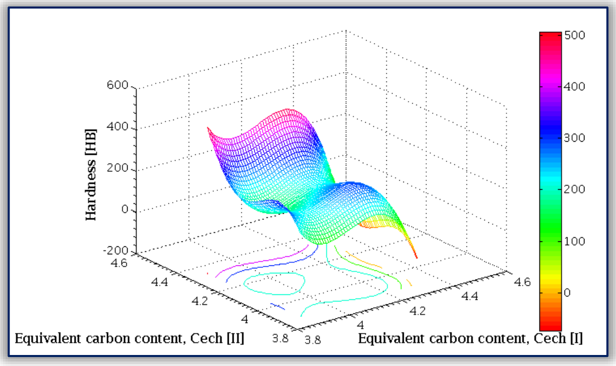


Figure 25. Regression surface, case of HB=f($C_{ech(I)}$,$C_{ech(II)}$)

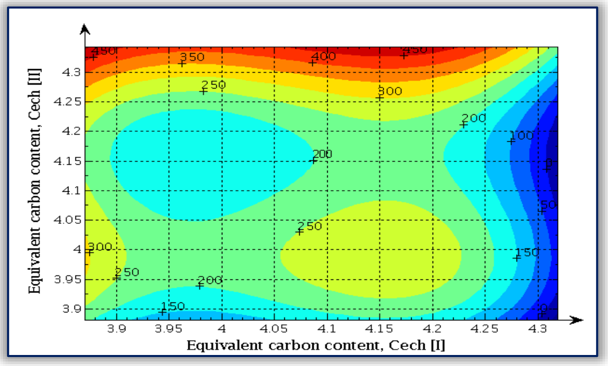


Figure 26. Correlation diagram, case of HB=f($C_{ech(I)}$,$C_{ech(II)}$)

For gray iron destined to brake shoes casting the equivalent carbon content (CE) concept is used to understand how alloying elements affect the casting behavior. It is used as a predictor of strength in cast irons because it gives an approximate balance of austenite and graphite in final structure. The carbon equivalent is invaluable in technological analysis and it is used in empirical formulas. To determine the equivalent carbon content in the cast irons the following formulas are used:

$$C_{ech\ (I)} = [C] + 0.33\ [Si] + 0.33\ [P] - 0.027\ [Mn] + 0.4\ [S] \quad (1)$$

$$C_{ech\ (II)} = [C] + 0.33\ ([Si] + [P]) \quad (2)$$

Thus, the total carbon equivalent of the cast iron consists of the carbon content and the carbon equivalents for each additional element. The carbon equivalents are usually determined experimentally.

The performed study had in view to obtain correlations between the hardness of the cast iron brake shoes and its chemical composition, defined by basic and the representative alloying element (phosphorous). The data revealed small variations of the hardness, which is due to variations in the narrow limits of the chemical composition. The values of the hardness are within the range 197–240 HB being in accordance with the international standards. The chemical and structural homogeneity of the shoes material lead to small variations of the values for the hardness (on both side surfaces and in the cross–section) what will find, finally, in the brake shoe's durability. There is a difference of hardness between the cross–section and the center section's measurement, which was explainable by the conditions of the solidification process, due to the cooling rate.

The values processed were made using Matlab calculation program. Technological engineers and brake shoe's manufacturers can interpret these regression surfaces, belonging to the three–dimensional space, and the correlation diagrams, belonging to the bi–dimensional space, presented in Figures 7–26. By analyze of the results of the experimental research upon a number of 100 charges of phosphorous cast iron brake shoes may be concluded the following:

≡ the chemical composition of iron used in the manufacture of the brake shoes ensure their hardness within the limits set by the standards.
≡ the correlation diagrams clearly results the influence of the content of Carbon, Manganese and Silicon on the hardness of the brake shoes;
≡ the level curves, obtained into the correlation diagrams allow us to choose the independent parameters (Carbon, Manganese and Phosphorous) in such a way as to obtain a desired value of hardness.

## 5. CONCLUDING REMARKS

This paper reviews key aspects of brake shoes material and presents an analysis of the influences of chemical composition upon their hardness. Using the double correlations variation boundaries for the chemical composition, in view the obtaining the optimal values of the hardness of brake shoes, are obtained. The partial results and evidence obtained by actual experiments are presented.

The materials used in the railway breaking components manufacturing may constitute one of the main research directions. In the case of the wheels, was reached the monobloc alloy steel wheel solution, with limited content of carbon and manganese, treated to a depth in ranging between 30–50 mm from the contact surface, which can lead to the increased sustainability. But in the case of the brake shoes related investigations, they could give no solutions with the character of the generalization, due to the heavy working regime (which involve environmental factor, temperature regimes, vibration and impact, etc.), but also due to the complexity of the concomitant wear phenomenon in the brake shoe–wheel system.

Unlike cast iron brake blocks, composite brake blocks are manufactured from a mix of up to 25 different metallic and organic substances. Every manufacturer uses a specific mix, so every type of pad must be considered as a separate product. This creates additional requirements, especially when it comes to replacing one type of brake block with another. Wear of wheels that are braked with composite blocks is higher than wear of wheels that are braked with cast iron blocks. Therefore, wheels with composite brake blocks last shorter. Moreover, wear of composite brake blocks is lower than wear of cast iron blocks. Therefore, composite brake blocks last longer. Increased life cycle costs of freight wagons are a disadvantage of composite brake blocks. In cooperation with railway operators and brake system suppliers, the rail vehicle manufacturers develops on optimized friction surface combinations for cast iron shoes and steel wheels, while taking into consideration customer technical specifications, suitable for passenger trains and freight wagon applications. So ordinary cast iron brake shoes are generally used for low–speed operation of passenger trains. For cast iron brake used in high–speed train, we can improve the performance by increase the content of phosphorus or add some alloy element. In the rolling stock, a brake shoe of phosphoric cast iron had a wear resistance and a higher friction coefficient, therefore, phosphorus was a very important element for the performance improvement of brake shoe. A cast iron of high phosphorus content, intended especially for the manufacture of brake shoes, offers good wear resistance.

To analyze the metallurgical processes is used, mainly, the statistical fundamental methods that permit to draw conclusions, from the observed values, about the repartition of the frequencies of various parameters, about their interaction, about verification validity of certain premises, and about the research of the dependencies among different parameters. In this sense, the realization of optimum chemical compositions of the cast–iron can constitute a technical efficient way to assure the exploitation properties, the material from which the brake shoes are manufactured having an important role in this sense. Therefore, the realization of an optimal chemical composition can constitute a technical efficient mode to assure the exploitation properties, the material from which the shoes are manufactured having an important role in this sense. From this point of view is applied the mathematical analysis, taking into consideration the collected industrial data. Moreover, durability in exploitation is extremely current, both for immediate practice, and for the scientific research attributed to the cast–iron used in brake shoes manufacturing.

Thus, have been searched as shoe's material, irons and alloys, which present a higher friction coefficient, constantly with the railway speed and, at the same time, a reduced wear speed for the breaking components. Moreover, obviously, all at the possible lowest cost. In these conditions, the research has shown that the irons remain as preferential material for the brake shoes, as demonstrated on both the passenger wagons, as well as for the freight wagons. Along with the gray irons (with the lamellar or nodular graphite), with high levels of phosphorus (above 0.8–1.1%), have given good results in exploitation, increasing resistance to wear and reducing the braking path without increasing the wheels wear. These favorable tribological effects by the difference of the smoother structure and with a more overlapping of eutectic phosphorous network are explained. Has been demonstrated too, the superiority of the irons with high phosphorus content, the operating conditions confirming these allegations.

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