Evaluation of Grindability Behaviors of Four Different Solid Fuels Blending by Using the Hardgrove Mill

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http://doi.org/10.29227/IM-2019-01-06

Submission date: *11-07-2018* | Review date: *02-04-2019*

Abstract

Grindability measurements are widely used in mineral and coal processing industry to determine resistance of materials to comminution. Grindability measurement as testing methods can be divided into two general categories; the Bond and the Hardgrove grindabilities. Grinding characteristics of the mineral or coal blending have been studied by several researchers over many years and a wide range grinding variables has been investigated. In this study, because of the simplicity and the potential usage of the method for the determination of the grindability of coals and their blending in a comparative scale, a Hardgrove mill were used to investigated the grinding behavior of four different solid fuels and their blending. Grindability of four different solid fuels such as; petroleum coke, coke coal, lignite and bituminous coal and their binary, ternary and quaternary blending were investigated by the Hardgrove grindability test. The test results indicated that determine the existence of a very good relation between the Bond and the Hardgrove grindability of the fuels, and relationship between experimental and calculated HGI values of the fuels blending were also shown as a very good. However, there is not obtain a good relation between proximate analysis results of the solid fuels and HGI values of fuels blending.

Keywords: coal; coke; petroleum coke; fuels; hardgrove grindability; bond grindability; fuel blending

Introduction

In grinding process of materials, the yearly megawatt hour's amount to several hundred millions in terms of the energy expended. Many expressions of grindability have been proposed over the years, but of these two of them have come into prominence because they have become the recognized basis for design of certain types of mill. One of them is the Hardgrove grindability index, associated mainly with vertical spindle mills and the other is the Bond's grindability index, associated with tumbling mills (McIntryre and Plitt, 1980; Prasher, 1987).

The Bond grindability method is included in category one and widely used to determine grindability of minerals in mineral processing industry. However, this method is both excessively time consuming and susceptible to procedural errors because of the intensity of the experimental steps. The Hardgrove Method for coal can be given as an example to be second type of test. The main advantage of Hardgrove method is its simplicity to perform. However, Hardgrove method does not give any information about energy consumption of the mill. The Hardgrove grindability for lignite or other heterogeneous materials can be applied only as a qualitative grindability characteristic, for example, to categorise them as difficult, easy or mediocre grindable (Prasher, 1987; Csöke et al., 2003).

Coal grindability usually measured by Hardgrove Grindability Index (HGI) is of great interest since it is used as a predictive tool to determine the performance capacity of industrial pulverisers in cement factories and power station boilers. Although the HGI testing device is not costly, it is tedious to determine the grindability index experimentally. Therefore there exists an interest to predict HGI values from proximate analysis. However, the test does suffer from some limitations. For example, the measurement can be insensitive to the heterogeneous properties of coal that arise from different mineral contents, maceral constituents, moisture contents and levels of maturity etc. It is difficult to predict the HGI based on some basic coal quality, such as proximate analysis. As such, it often gives misleading results to understand and explain properties emerging from other analyses and testing. Therefore, it is necessary to predict the grinding behaviour of the individual components in blends to make the right product with the desired size distribution and composition (Cho and Luckie, 1995; Vutharluru et al., 2003; Chalgani et al., 2008; Malav et al., 2008).

Coal, one of the solid fuels, is a heterogeneous substance which is consisted of combustible (organic matter) and non-combustible (moisture and mineral matter) materials. The grindability of coal is an important practical and economic property to coal handling and utilisation aspects, particularly for pulverised coal fired utilities. In general, coal grindability characteristics reflect the coal hardness, tenacity, and fracture which are influenced by coal rank, petrography, and the distribution and the types of minerals. Therefore, the prediction of grindability index on the basis of the proximate analysis may not give accurate result if the age, rank and petrographic composition of coals are not similar (Vutharluru et al., 2003; Chalgani et al., 2008; Ozbayoglu, et al., 2008).

Some researchers have investigated the prediction of HGI based on proximate analysis, petrography, and vitrinite maximum reflectance of solid fuels with using linear, nonlinear multivariable regression and generalized regression neural

Tab. 1. Proximate analysis values of coal samples used experiments (base original)
Tab. 1. Analiza techniczna próbek węgla wykorzystywanych w eksperymentach

Sample Name	Moisture (%)	Ash (%)	Fixed Carbon (%)	Volatile Matter (%)	N et Calorific Value (kcal/kg)
Coke	7.96 1	1.32 7	9.97 0	.75	5528
Petroleum Coke	5.66 0	.60	83.14	10.66	7993
Lignite 2	5.07 2	2.70 2	7.69 2	4.97	3376
Bituminous Coal	14.14	11.70	52.50	21.66	5628

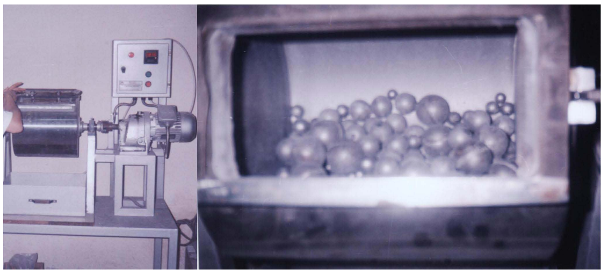

Fig. 1. The Bond ball mill
Rys. 1. Młyn kulowy Bonda

network. The result of these researches, there are several formulas available for predicting the Hardgrove grindability of coal, most of them are linear and do not simultaneously take into consideration most of the relevant factors (Li et al., 2005; Ozbayoglu et al., 2008).

Blending is another parameter which influences the grindability of a given coal. There have been some investigations in the past on the HGI of coal blends in relation to the additivity of the HGI, and although some coals show additivity, this is not usually the case. There is no general method of predicting the HGI of a coal blend, which must be determined experimentally on a case to case basis (Vutharlu et al., 2003).

The subject of this study was about the effects on the grindability value of proximate analysis values (Moisture, Ash, Volatile Matter, Fixed Carbon and Net Calorific Value) on solid fuels, and the effects on the grindability of binary, triple and quaternary blending of four different solid fuels. For this purpose, the solid fuels that called lignite, bituminous coal, coke and petroleum coke, used in the Votorantim Cement Factory in Corum (Turkey), were tested. In these tests, the Hardgrove mill has been used to determine the grindability index. In this research, simple linear regression techniques for the estimation of Hardgrove grindability index (HGI) values of solid fuels are studied.

Material and methods

Material

Four different fuel samples, called the lignite, the bituminous coal, the coke and the petroleum coke, taken from fed storage area belongs to Votorantim cement factory in Corum (Turkey), were used as the experimental materials. The proximate analyses of solid fuel samples used in experiments were presented in Table 1.

Method

In this study, firstly, the Bond grindability and the Hardgrove grindability tests were applied on the individual samples. Later, only the Hardgrove grindability tests were performed for blending operations.

The Test of Standard Ball Mill Bond Grindability

The standard Bond grindability test is a closed-cycle dry grinding in a standard ball mill (30.5x30.5 cm) and screening process, which is carried out until steady state condition is obtained. The standard Bond mill used in the experiments was shown in Figure 1. This test was described as follow (Bond and Maxson, 1943; Deniz and Ozdag, 2003; Deniz, 2004; Deniz et al., 2013):

The material is packed to 700 cc volume using a vibrating table. This is the volumetric weight of the material to be used for grinding tests. For the first grinding cycle, the mill is started with an arbitrarily chosen number of mill revolutions. At the end of each grinding cycle, the entire product is discharged from the mill and is screened on a test sieve (Pi). Standard choice for Pi is 106 micron. The oversize fraction is returned to the mill for the second run together with fresh feed to make up the original weight corresponding to 700 cc. The weight of product per unit of mill revolution, called the ore grindability of the cycle, is then calculated and is used to estimate the number of revolutions required for the second run to be equivalent to a circulating load of 250%. The process is continued until a constant value of the grindability is achieved, which is the equilibrium condition. This equilibrium condition may be reached in 6 to 12 grinding cycles. After reaching equilibrium, the grindabilities for the last three cycles are averaged. The average value is taken as the standard Bond grindability value (G_{bg}).

$$G_{bg} = \frac{P}{n} \qquad (1)$$

where, G_{bg} is the Bond grindability index of sample (g/rev); P is the net amount of ground products, (g), and n is revolution number of the Bond ball mill,

The Bond work index values (Wi) are calculated from Eq. (2).

Tab. 2. Status of binary, triple and quaternary blending of four different solid fuels using in the experiments

Tab. 2. Parametry mieszanek dwu, trzy i czteroskładnikowych paliw stałych wykorzystywanych w eksperymentach

Blending	Coke (A)	Petroleum Coke (B)	Lignite (C)	Bituminous Coal (D)
1. Blending	A/4	B/4	C/4	D/4
2. Blending	---	B/3	C/3	D/3
3. Blending	A/3	B/3	C/3	---
4. Blending	A/3	---	C/3	D/3
5. Blending	A/3	B/3	---	D/4
6. Blending	---	---	C/2	D/2
7. Blending	A/2	B/2	---	---
8. Blending		B/2	C/2	---
9. Blending	A/2	---	C/2	---
10. Blending	A/2	---	---	D/2
11. Blending	---	B/2	---	D/2

$$W_i = 1.1 * \frac{44.5}{P_i^{0.23} * G_{bg}^{0.82} * \left[\left(10/\sqrt{P_{80}}\right) - \left(10/\sqrt{F_{80}}\right)\right]} \quad (2)$$

where, W_i is the standard Bond work index, (kWh/t); P_i is test sieve size (106 μm); G_{bg} is the Bond standard ball mill grindability, (g/rev); P_{80} and F_{80} are the 80% of cumulative undersize curve of feed and product (μm), respectively.

Hargrove Grindability Index (HGI) Test Method

The Hardgrove grindability index (HGI) of coal is an important technological parameter in understanding the behavior of the grinding of coal. The design of the vertical spindle mill is mainly depended on the HGI. Although the device for testing of HGI is not costly, the measuring procedure to get a HGI value is toilsome and time consuming. In addition, it is not a routine testing item in coal fired power and cement plants which used vertical spindle mills (Peisheng et al., 2005).

In the United States, the HGI method is described in ASTM D409 "Standard Test Method for Grindability of Coal by the Hardgrove-Machine Method" (ASTM, 1951). This method consists of grinding a sieved sample in a grinder with defined dimensions and grinding energy, measuring the sieve size of the remaining product, and comparing the result with standard coal samples to produce the relative grindability index. A high HGI value of a coal indicates that the coal is easy to grind. The most often reported limitations of the HGI test include that the parameter is non-linear (e.g. HGI values changing from 40 to 50 can cause much more difference in grindability or mill capacity than from 90 to 100), not-additive as in cases of blend coals, and affected significantly by moisture content and thus pretreatment of coal samples. Some modifications of the standard test results in more confusion, e.g. the same coal may have different HGI test results.

The ASTM (1951) Hardgrove procedure was carried out, i.e. the test feed is 50 g sample of coal, which has been prepared in a specific manner and which has a limited particle size range, 1.18 x 0.6 mm, is placed in a stationary grinding bowl in which eight steel balls can run in a circular path. A loaded ring is placed on top of the set of balls with a gravity load of 29 kg. The machine is run (for 3 minute) for 60 revolutions of the mill at speed of 20 rev/min. The top is removed and the ground coal removed. This coal is sized and the quantity less than 75 microns recorded. This is converted to a HGI value using a calibration graph.

In this study, a mill with 5E-HA-60x50 model of the CKİC trademark, a made in Chinese, was used as the Hardgrove mill as shown in Figure 2a. The calibration graph created for the mill was also given in Figure 2b. Hardgrove Grindability Index tester (5E-HA-60x50 model) by using in experiments is distinguished from classical Hardgrove grindability testers in terms of advantage properties such as high automation, compact structure and intelligence control.

Experiments

Firstly, standard Bond grindability tests were obtained for four solid fuel samples, and Bond work indexes were calculated. Result of tests, the Bond grindability values of solid fuel samples (coke, petroleum coke, lignite and bituminous coal) were appeared 0.303 g/rev, 0.815 g/rev, 0.964 g/rev and 0.958 g/rev, and the Bond work index values of fuel samples were calculated 43.32 kWh/t, 24.13 kWh/t, 16.92 kWh/t and 17.71 kWh/t, respectively. Secondly, the Hardgrove grindability tests were obtained for four solid fuel samples, and Hardgrove grindability index values of fuel samples were calculated 26.15, 54.18, 63.56 and 69.56, respectively. Then, a good calibration has been established between the Bond and the Hardgrove grindabilities at the beginning of the tests as shown in Figure 3a.

Variation of Experimental and Calculated Hardgrove Grindability Indexes of Solid Fuels Blending

The Hardgrove grindability index of solid fuel blending (binary, triple and quaternary) were investigated for prediction from the weighted average of the Hardgrove grindability indexes of the individual fuels in the blending by using 11 different blending samples from four different solid fuels. The states of the mixture samples of 11 different blending used in the experiments were given in Table 2.

The test results were analyzed using the method of least squares regression. For the blending of four different fuel samples; the experimental grinding characteristic results of binary, triple and quaternary blending were almost similar results to that calculated HGI values. The relationships be-

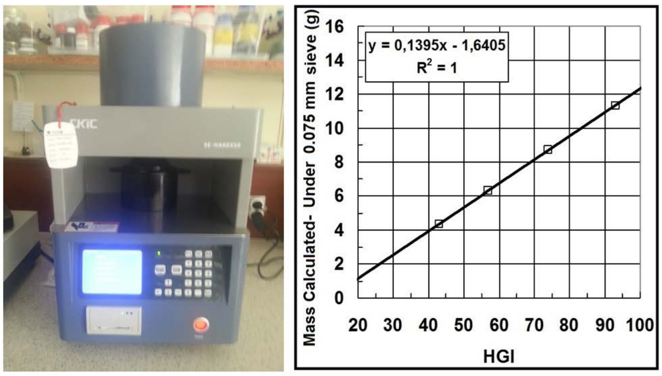

Fig. 2. Hardgrove mill (a) and Calibration graph (b) used in the experiments
Rys. 2. Młyn Hardgrove'a (a) i krzywa kalibracji (b) stosowane w eksperymentach

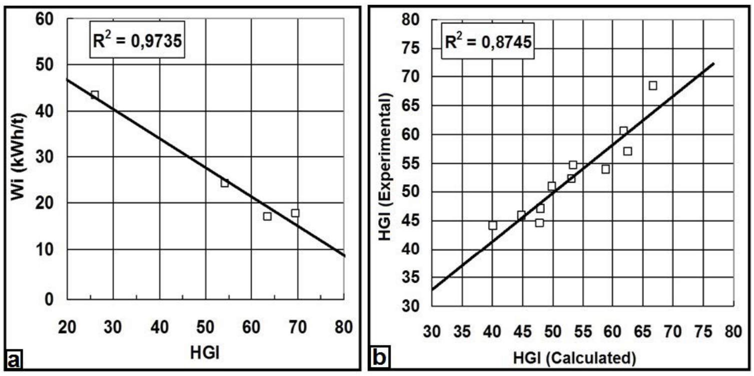

Fig. 3. (a) Relationship between Gbg and HGI value for four different solid fuels (b) Comparison of experimental and calculated HGI value for solid fuels
Rys. 3. (a) Związek między wartością Gbg i HGI dla czterech różnych paliw stałych (b) Porównanie doświadczalnej i obliczonej wartości HGI dla paliw stałych

tween calculated HGI values and experimental HGI values were presented with a good correlation (Figure 3b).

Hardgrove grindability index (HGI) of fuel blending showed similar as calculated HGI values of the weighted average values of the individual coals. In this study, a general conclusion could be drawn on the grindability behaviour of coal blends in contrast to Vutharlu et al. (2003). Similarity in grindability indexes have been observed from different blending of the same fuels.

The Hardgrove grindability index of binary, triple and quaternary fuel blends could be predicted from the weighted average of the Hardgrove grindability indexes of the individual fuels in the blending. The reason for this is unclear, but this was especially more meaning in the case of blending a lignite with a petroleum coke. However, this may have important implications in combustion performance as the feed to a pulverised-fuel cement factory using these types of blends could be quite different than specified. One potential method of avoiding this problem would be to blending the coals after grinding.

The Relationships of Between Proximate Analysis Values and Hardgrove Grindability Indexes of The Solid Fuels and Their Blending

The Hardgrove grindability indexes (HGI) were correlated with corresponding proximate analysis values (moisture, ash, volatile matter, fixed carbon and net calorific value). As shown in Figure 4, the HGI values of binary, triple and quaternary blending were no significant correlation result to that proximate analysis values (moisture, ash, fixed carbon and net calorific value) with blending contents of solid fuel samples except volatile matter content. The reason for the lack of good correlations is probably due to the fact that grinding is a complex phenomenon and depends on more than a fuel proximate analysis property. On the other hand, the relationship between HGI values and volatile matter content were presented with a good correlation. Volatile matter content has been found to be not only affected by quality of solid fuels content but also grindability of solid fuel.

Linear regression techniques by Windows Excel package were used for predicting the HGI values for the specified solid proximate analysis values. The relationships between HGI and proximate analysis values (moisture, ash, volatile matter, fixed carbon and net calorific value) for solid fuel samples are shown in Figure 4. It was found from statistical analysis that, the higher the fixed carbon and the net calorific value content in the solid fuels, the less the HGI will be. On the contrary, the higher the moisture, ash, volatile matter content in solid fuels, the higher the HGI will be. But the correlation between proximate analysis and HGI in solid fuels is nonlinear. The prediction equation of HGI reported in literature, which is based on proximate analysis of fuels and linear regression method, may not be correct for the solid fuels in this study.

Addition, the results show that there was no also acceptable correlation coefficient between the Hardgrove grindability index and the proximate analyses of the solid fuels. The insignificant results show that fuels' proximate analysis alone cannot be used to predict HGI. Examinations of the graphs in

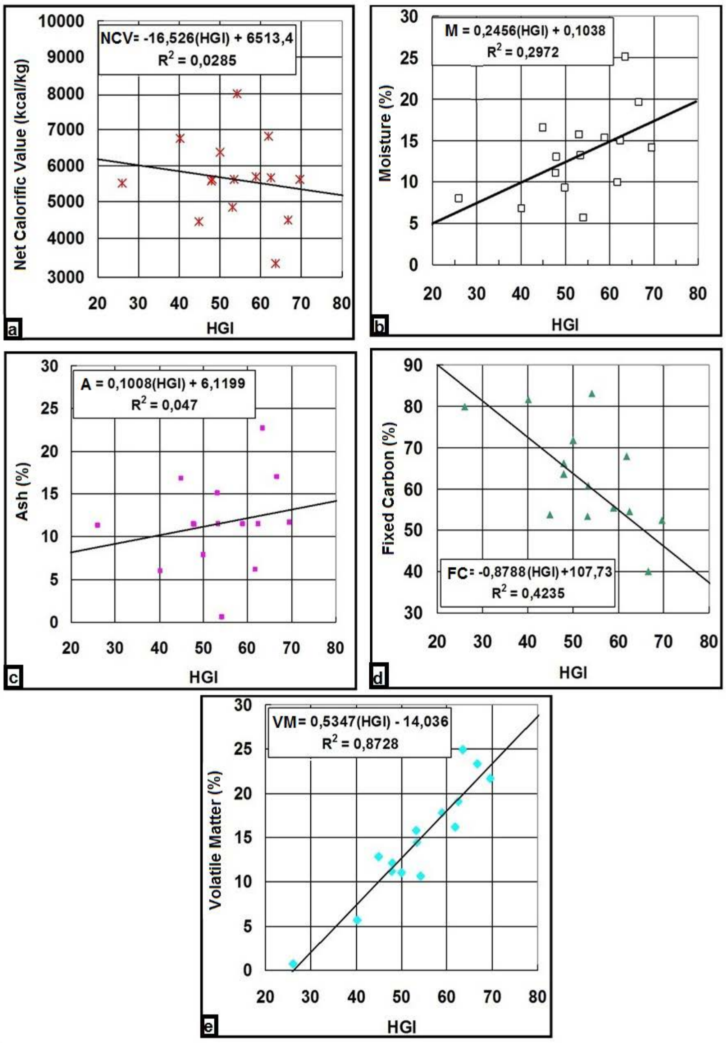

Fig. 4. Relationships between HGI and proximate analysis values (Net calorific value (a), moisture (b), ash (c), fixed carbon (d) and volatile matter (e))

Rys. 4. Zależności między HGI a przybliżonymi wynikami analizy technicznej analizy (wartość opałowa netto (a), wilgotność (b), popiół (c), stały węgiel (d) i substancje lotne (e))

Figure 4 demonstrated that moisture, ash, fixed carbon and net calorific value have no relationship to the Hardgrove grindability index. The best relationship was with volatile matter content of solid fuels and their blending. Volatile matter shows some promise as a predictor, but moisture, ash, fixed carbon and net calorific value were present in such low quantities, and their inclusion in the equation contributes little if anything to the overall regression. Solid fuels having high volatile matter content are found difficult to grind whereas coals which have medium and low volatile matter content are easy to grind. The different petrographic origin in solid fuel also exercises appreciable influence on the grindability. Consequently, there is not meaning that the better quality of solid fuels have, the easier grindability.

Variations in Hardgrove grindability indexes have been observed from different blending of the fuels are possibly due to varying origin as well as proximate analysis contents in the tested solid fuel samples. Hence, it is a poor correlation with HGI values and proximate analysis values. As similar pointed out by Ozbayoglu et al. (2008), it appears that there is no general method of predicting the grindability of a solid fuel blend from proximate analysis contents of the tested solid fuel samples, which must be determined experimentally.

Conclusions

In this study, the effect of blending, an important factor in the grinding of solid fuels was investigated. In the first stage, the calibration between the Bond grindability index (G_{bg}) and the Hargrove grindability index (HGI) for solid fuels was studied, and the relationship between them was presented with a good correlation. In the second stage, the calibration between the calculated and the experimental Hargrove grindability indexes for solid fuels blending was studied, and the relationship between them was also presented with a good correlation. In the third stage, the relationship between HGI and proximate analysis values in the solid fuels blending were not presented with a good correlation.

The tests made on the blending contents of four different solid fuel samples showed that they have similar grinding for experimental and calculated HGI values versus blending content whereas they have generally different grinding characteristics for proximate analysis values.

Hardgrove grindability tests on blending of solid fuels of varied volatile matter content showed an effect of volatile matter content on HGI. HGI values increases with increasing volatile matter content in the samples. Almost good correlation with volatile matter was found for all the samples tested; however, the range of variation of grindability with other proximate analysis content (moisture, ash, fixed carbon and net calorific value) varied among blending of the tested samples.

As a conclusion of this study, the determination of grindability of each solid fuel and each fuel blending versus proximate analysis values must be still done because they have different grindability characteristic in terms of their proximate analysis values.

Experimental results obtained from the present study would be further developed by the collection and analysis of different solid fuel samples from Votorantim Corum cement factory. This would prove to be valuable for fuel producers as well as solid fuel users in understanding the variations in HGI in terms of fuel compositions (origin and proximate analysis values) for a particular fuel.

Acknowledgment

This study was carried out with the research project (Project No: MU19005.16.01) under the 19005 University-Sector Cooperation supported by the Hitit University Scientific Research Fund (BAP).

In addition, I would like to thank the Çorum Votorantim Cement Plant officials and employees for their assistance during this research.

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Ocena podatności na mielenie czterech różnych mieszanek paliw stałych za pomocą Młynka Hardgrove

Pomiary podatności na mielenie są stosowane w przemyśle przeróbki minerałów i węgla w celu określenia odporności materiałów na rozdrabnianie. Metody testowania można podzielić na dwie ogólne kategorie; oznaczenie podatności na mielenie wg Bonda i Hardgrove'a. Charakterystyka mielenia mieszanek mineralnych lub węglowych była badana przez wielu badaczy przez wiele lat i obejmowała szeroki zakres danych. W artykule przedstawiono wyniki oznaczenie podatności na mielenie według Hardgrove'a z uwagi na jej prostotę i potencjalne wykorzystanie jako metody porównawczej. Zbadano podatność na mielenie czterech różnych paliw stałych i ich mieszanek takich jak: koks naftowy, węgiel koksowy, węgiel brunatny i węgiel bitumiczny oraz ich mieszanki dwuskładnikowe, trójskładnikowe i czteroskładnikowe. Wyniki testów wskazywały, że istnieje związku między wynikami testu Bonda i Hardgrove'a (HGI). Przedstawiono porównanie wyników teoretycznych i laboratoryjnych. Stwierdzono również żebrak korelacji pomiędzy wynikami analizy technicznej paliw i oznaczeniem podatności na mielenie.

Słowa kluczowe: węgiel; koks; koks naftowy; paliwa; indeks Hardgrove'a, podatność mielenie, mieszanki paliwowe