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Studies of the relationship between coal petrology and grinding properties

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Abstract

The maceral and microlithotype composition of selected coals has been investigated with respect to the grinding properties, specifically Hardgrove grindability index (HGI), of the coals. The study expands upon previous investigations of HGI and coal petrology by adding the dimension of the amount and composition of the microlithotypes. Coal samples, both lithotypes and whole channels, were selected from restricted rank ranges based on vitrinite maximum reflectance: 0.75–0.80% R_{max}, 0.85–0.90% R_{max} and 0.95–1.00% R_{max}. In this manner, the influence of petrographic composition can be isolated from the influence of rank. Previous investigations of high volatile bituminous coals demonstrated that, while rank is an important factor in coal grindability, the amount of liptinite and liptinite-rich microlithotypes is a more influential factor. In this study, we provide further quantitative evidence for the influence of microlithotypes on HGI and, ultimately, on pulverizer performance.

Keywords: Coal; Hardgrove grindability; Kentucky; Petrology; Microlithotype

1. Introduction

The relationship between Hardgrove grindability index (HGI) and coal petrology was explored by Hower et al. (1987) and Hower and Wild (1988, 1994). Hower (1998) summarized previous work at the Center for Applied Energy Research, as well as work conducted in other laboratories, and the reader is referred to that paper for an extensive discussion of the complexities of the relationship between the HGI test and petrographic parameters.

Studies of lithotype sequences from Kentucky coal seams, each ideally an isorank set, showed significant differences between lithotypes. An extreme case is illustrated by an 11-lithotype sequence from the Harlan coal bed, Harlan County, KY (Fig. 1). The HGI range of 39 units is the largest we have observed in any of the high volatile bituminous coals of Kentucky. The number is skewed somewhat by virtue of the 64 HGI value being from a relatively high ash (26.6% dry ash) lithotype. It is certainly possible that the mineral matter within that lithotype contributed to the development of planes of weakness, leading to an higher-than-expected HGI. Expected or not, the range is real and does reflect the hardness variation in the coal bed, as seen first by the continuous miner (Hower and Lineberry, 1988) and later by the pulverizer at the power plant (Hower, 1998).

Hower and Wild (1988) examined 656 Kentucky coals with proximate and ultimate analyses, petro-

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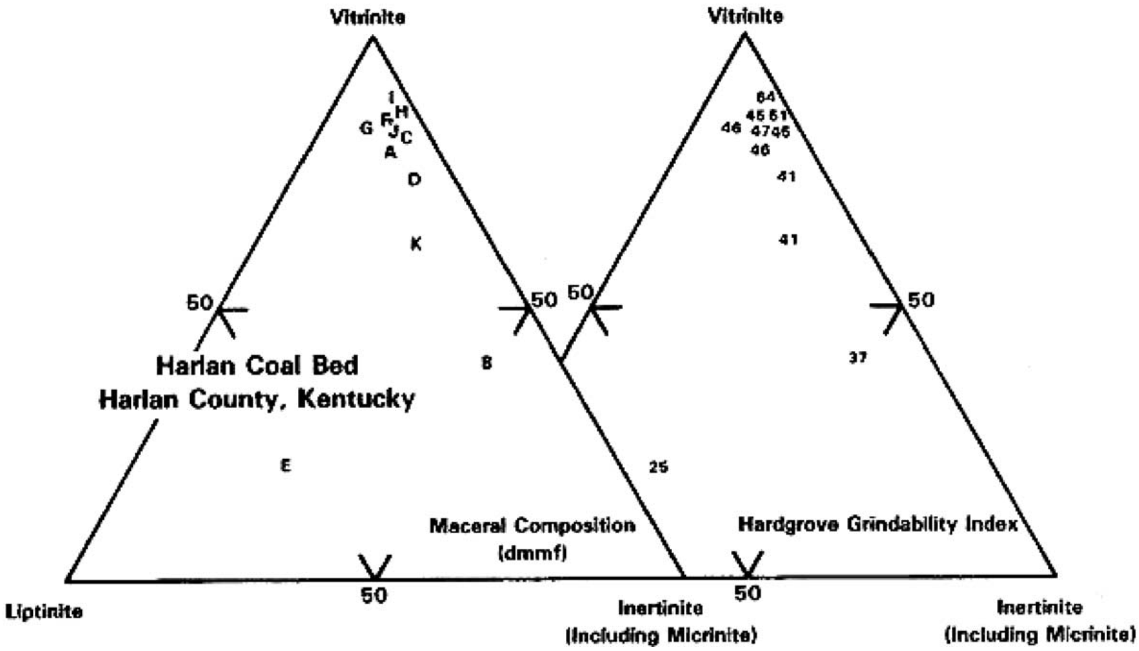

Fig. 1. Generalized maceral composition, not including mineral matter, and Hardgrove grindability index, also plotted on a maceral-group basis, for lithotypes from the Harlan coal bed, Harlan County, KY (from Hower and Wild, 1988).

graphic analyses, including vitrinite maximum reflectance and HGI. Regressions of HGI vs. various properties were statistically significant at the 95% level for both eastern and western Kentucky. For eastern Kentucky, the subject of the investigations in this paper, they found that, for 473 samples, HGI could be predicted on the basis of three variables, as follows:

$$\mathrm{HGI} = 37.41 - 10.22\ \ln(\mathrm{liptinite}) + 28.18R_{\mathrm{max}} + S_{\mathrm{total}}. \quad (1)$$

HGI increases by two units for every 0.1% increase in reflectance, or 12 units for the 0.44–1.12% R_{max} range found in eastern Kentucky. The HGI range is actually 20–76; therefore, rank cannot be the only variable. Considering the liptinite range of 1.2–54.1% for all of the eastern Kentucky coals in the study, the predicted HGI range would be 41 HGI units (given equal vitrinite reflectance). The combined influence of liptinite and reflectance in understanding the HGI of eastern Kentucky coals can be seen on Fig. 2. Basically, higher rank coals within the rank range studied have a higher HGI for a given liptinite content. The difference between the two rank trends converges at higher liptinite contents.

Hower et al. (1987) examined the relationship between HGI and the maceral and microlithotype composition (Table 1) for collections of lithotype samples from two eastern Kentucky mines. The coal rank for the two sets was different, but each set was considered to be an isorank series. For the lower rank

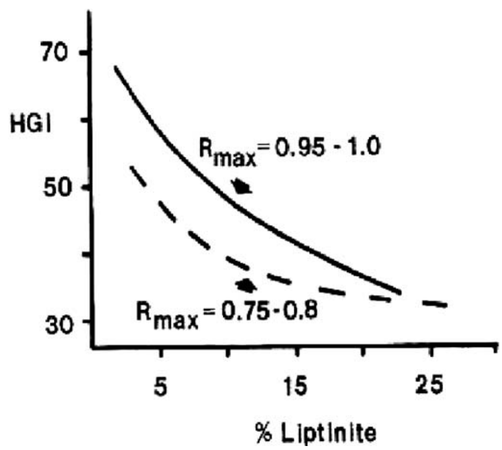

Fig. 2. HGI vs. liptinite percentage for eastern Kentucky coals in the 0.75–0.80% and 0.95–1.00% R_{max} ranges (after Hower and Wild, 1988).

Table 1
Maceral composition of microlithotypes

Monomaceral microlithotypes	
Vitrite	vitrinite (V) > 95%
Liptite	liptinite (L) > 95%
Inertite	inertinite (I) > 95%
Bimaceral microlithotypes	
Vitrinertite	V + I > 95%
Clarite	V + L > 95%
Durite	L + I > 95%
Trimaceral and mineral-rich microlithotypes	
Duroclarite	V > L, I; with each group >5%
Clarodurite	I > V, L; with each group >5%
Vitrinertoliptite	L > I, V; with each group >5%
Carbominerite	20–60% silicates or carbonates by volume or 55–20% sulfides by volume

(R_{max} = 0.78%) collection of 44 samples from the Coalburg and No. 5 Block coals, Martin County, KY, the following equation with an r^2 of 0.67 was developed:

$$\mathrm{HGI_{MC}} = 37.80 + 0.15\ \text{vitrite} + 2.40\ \text{liptite} - 1.21\ \text{vitrinertoliptite} - 0.21\ \text{carbominerite} + 0.32\ \text{ash}. \qquad (2)$$

For the higher rank (R_{max} = 0.87%) collection of 34 samples from the Leatherwood coal bed, Letcher County, KY, the following equation with an r^2 of 0.84 was developed:

$$\mathrm{HGI_{BD}} = 49.29 - 0.25\ \text{durite} + 0.40\ \text{vitrinertite} - 0.18\ \text{duroclarite} - 0.28\ \text{clarodurite} - 1.09\ \text{vitrinertoliptite} + 0.11\ \text{ash}. \qquad (3)$$

The positive sign for liptite in the first equation is counterintuitive. Liptinite is a tough constituent in coals, contributing to the hardness and resistance to grinding of liptinite-rich microlithotypes. The authors noted that liptinite occurred in small quantities in the coal and the liptinite term was the last to enter the stepwise multiple regression. In general, however, the vitrinite-rich and mineral matter-rich mono- and bimaceral microlithotypes make a positive contribution to HGI.

In this study, we re-examine the reflectance ranges plotted by Hower and Wild (1988) (Fig. 2, this paper) using the approach adopted in the Hower et al. (1987) paper. For the 0.75–0.80% R_{max} range, the Coalburg and No. 5 Block samples analyzed by Hower et al. (1987) were added to the current sample set. An additional rank range, 0.85–0.90% R_{max}, was added to incorporate the Leatherwood samples from the previous study. The overall objective of the investigation was to expand the petrographic information for coals within relatively narrow rank ranges, as defined by vitrinite maximum reflectance, to enable better understanding of the petrographic basis for coal grindability.

2. Procedure

Samples of eastern Kentucky coals in three reflectance ranges, 0.75–0.80%, 0.85–0.90% and 0.95–1.00% R_{max}, were selected for combined maceral/microlithotype analysis. All samples had been previously prepared as particulate pellets, with vitrinite maximum reflectance performed for previous characterization. Statistical analyses were conducted using the SPSS software package (http://www.spss.com/; accessed 25 Nov. 2002).

3. Discussion

3.1. Statistical considerations

Equations were generated and applied to a large sampling of data and yield promising descriptive results. Caution had to be used in selecting the variables, because of the great inter-dependence between the variables. In many cases, a variable would be a relatively strong contributor to HGI, but would be more strongly correlated to the other variables that were influencing HGI. Including these variables inflates the R^2 of the model, but does not necessarily mean that the model more accurately describes HGI.

In order to generate a solid realistic predictive equation for a set of data, a fairly uniform behavior among the samples is needed. Samples that have extremely high levels of mineral matter tended to show the strongest deviations from normal behavior.

A good tool for combating these discrepancies was to consider only low-ash coals. This is successful because it is a single property that is highly correlated to all of the mineral variables (carbominerite [CM], silicates [SIL], minerals [MIN]).

For this analysis, the backward regression was used. This method of performing regressions is well suited to the data set. There are many variables that potentially influence HGI and there are relatively few samples for each reflectance range in comparison to potential variables. It is therefore beneficial to start by considering all possible variables, and eliminating those that do not have any real effect as opposed to starting with a forward regression.

Also, there is evidence that even within the narrow reflectance ranges analyzed, reflectance is still somewhat an influential property. While never being considered significant at the 0.01 or 0.05 level (two tailed), the reflectance of the sample within the range had a non-random effect on HGI.

3.2. 0.75–0.80 reflectance range

This range included 45 samples, taken from a broad variety of seams (Coalburg, Leatherwood, River Gem, Harlan, Path Fork and Francis). Attempting to describe the entire data set with one set of variables proved difficult. The best fit established used the variables carbominerite (CM), vitrite (VT), vitrininertoliptite (VL), clarodurite (CD), ash yield from the proximate analysis (ASH) and yielded an R^2 of 0.429:

$$\mathrm{HGI} = 35.554 - 0.143\ (\mathrm{ASH}) - 0.280\ (\mathrm{CD}) + 0.351\ (\mathrm{CM}) + 0.614\ (\mathrm{VL}) + 0.135\ (\mathrm{VT}). \quad (4)$$

The inability to describe the set's behavior was due in part to the different properties of low and high ash coals. High ash coals in this rank range have particularly abundant silicate or clay-like material, which has a tendency to artificially (disproportionally) increase the HGI of the sample. For the purposes of this study, a coal was considered to be a high ash coal if it yielded greater than 20% ash. There were 12 such samples in this reflectance range. When these samples were eliminated from the regression, a more meaningful description of the dataset was possible. Using the variables SIL, VT, duroclarite (DC), CD and ASH, the data could be described with an R^2 of 0.763:

$$\mathrm{HGI} = 47.766 - 0.446\ (\mathrm{ASH}) - 0.274\ (\mathrm{CD}) + 0.208\ (\mathrm{VT}) - 0.281\ (\mathrm{DC}) + 1.039\ (\mathrm{SIL}). \quad (5)$$

In this case, the elevated R^2 for the fit can be in part explained by reducing the total number of samples being evaluated, but is more the result of evaluating a set of samples with greater inner-consistency. Because of a strong correlation between high ash and mineral matter, the removal of the high ash coals gave less importance to the carbominerite variable and increased the influence of liptinite.

In addition to these 45 samples, 44 samples within the 0.75–0.80 reflectance range from a previous study (Hower et al., 1987) were taken into consideration. The two data sets were combined to gain a better understanding of the trends and regression models were plotted out for the collaboration. Using the same variables as before to describe the data set, an equation with an R^2 of 0.320 was generated:

$$\mathrm{HGI} = 37.213 - 0.026\ (\mathrm{ASH}) - 0.174\ (\mathrm{CD}) + 0.145\ (\mathrm{CM}) + 0.013\ (\mathrm{VL}) + 0.121\ (\mathrm{VT}). \quad (6)$$

At first glance, this seems to be a poor fit, but upon further consideration it can be expected. The initial fit was not very good to begin with, and adding more samples to a poorly described set does not guarantee improvement. This also is in agreement with the more random nature of coals of this rank range. It is therefore of particular importance to consider the 0.75–0.80 reflectance range without the high-ash samples. When this was done with the combined set of 66 samples, plotted on Fig. 3, with the high-ash samples excluded, we obtained an R^2 of 0.563 using the same variables as before:

$$\mathrm{HGI} = 44.051 - 0.083\ (\mathrm{ASH}) - 0.315\ (\mathrm{CD}) + 0.178\ (\mathrm{VT}) - 0.167\ (\mathrm{DC}) + 0.293\ (\mathrm{SIL}). \quad (7)$$

The improvement in the fit was significant, but not as much as when just the 33 samples were considered.

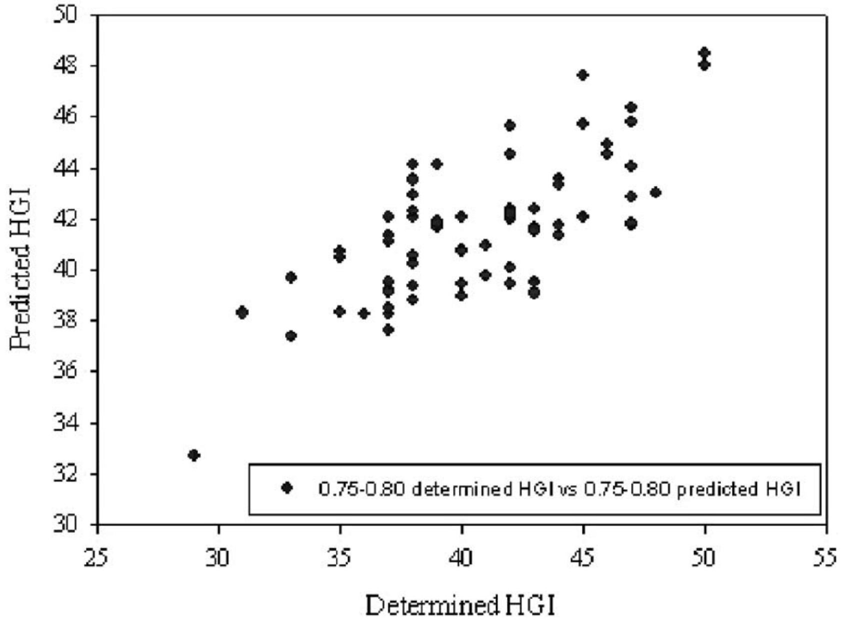

Fig. 3. Predicted vs. determined HGI for coals in the 0.75–0.80% R_{max} range.

The sample size of 33 was bordering on being too small to entail applying five variables to yield the fit, so it is possible that the 0.763 R^2 was slightly inflated. Also, slight differences in petrographic analysis could have caused the discrepancy. However, the two equations describing the data set bear strong similarities. The intercept of both equations fall at roughly the same location (47.77 as compared to 44.05). Also, while the coefficients undergo change from one equation to the other, the proportions in which the materials contribute do not change substantially.

3.3. 0.85–0.90 reflectance range

The 0.85–0.90 reflectance range data set consisted of 41 samples, taken from a more narrow variety of seams (36 of the 41 samples were from Pond Creek or Leatherwood; others were from Clintwood, Pond Creek Rider and Jellico). The best fit established used the variables vitrininertite (VI), durite (DU), DC, CD and CM, and yielded an R^2 of 0.681:

$$\mathrm{HGI} = 51.608 - 0.267\ (\mathrm{DU}) + 0.602\ (\mathrm{VI}) - 0.261\ (\mathrm{DC}) - 0.451\ (\mathrm{CD}) + 0.084\ (\mathrm{CM}). \tag{8}$$

The range was more easily described by one set of variables than the 0.75–0.80 reflectance range. Attributing to the increased ease in finding a descriptive equation could have been the fact that samples were taken from a more narrow range of seams, thus ensuring greater composition consistency amongst the samples.

Removing the high ash coals within this data set and applying the same logic to this range as was done in the 0.75–0.80 reflectance range did not yield the same kind of improvement in describing the data. Thirty-five samples were considered and an equation using the variables VI, DU, DC, CD and liptite (LP) yielded an R^2 of 0.679:

$$\mathrm{HGI} = 54.193 - 0.327\ (\mathrm{DU}) + 0.566\ (\mathrm{VI}) - 0.280\ (\mathrm{DC}) - 0.454\ (\mathrm{CD}) - 3.035\ (\mathrm{LP}). \tag{9}$$

Because of a strong correlation between high ash and mineral matter, the removal of the high ash coals gave less importance to the carbominerite variable and increased the influence liptinite.

In addition to the coals that were investigated in this study, a subset of 34 samples (from Hower et al.,

1987) within the 0.85–0.90 reflectance range was considered. When the two data sets were combined, the same variables (VI, DU, DC, CD and CM) as before, with an R^2 of 0.699, described an equation for predicting HGI:

$$\mathrm{HGI} = 54.438 - 0.316\ (\mathrm{DU}) + 0.494\ (\mathrm{VI}) - 0.329\ (\mathrm{DC}) - 0.366\ (\mathrm{CD}) + 0.025\ (\mathrm{CM}). \quad (10)$$

In this case, the slight improvement in the R^2 value is the result of the addition of more samples to the data set. The new equation compares favorably to the first. The most encouraging aspect of the two equations is that the same variables most accurately describe the data set. Also, while there are slight differences in the influence of each variable from equation to equation, the proportions remain the same. The y-intercept remains in roughly the same location (51.61–54.44); the signs of all the variables remain the same, with DU and DC having about the same influence, while CD has slightly more so; and VI has a strong influence comparatively. Also, in both instances, CM has a minuscule effect on HGI.

Once again, a consideration of the data set without the high ash samples was made. The addition of the Hower et al. (1987) data improved the fit of the equation, using the same variables as in the smaller data set (DU, VI, DC, CD and LP). The new reconsidered equation for the 66 samples produced an R^2 of 0.686 (comparison plotted on Fig. 4):

$$\mathrm{HGI} = 54.109 - 0.342\ (\mathrm{DU}) + 0.476\ (\mathrm{VI}) - 0.307\ (\mathrm{DC}) - 0.345\ (\mathrm{CD}) - 1.656\ (\mathrm{LP}). \quad (11)$$

The new equation considering all of the low-ash samples compares favorably to the first equation. The y-intercept is in virtually the same location and again the proportions of the influence that each variable holds on HGI are the same in each equation. The absolute values in each case are also very close to each other. This is an expected result of removing the high-ash samples. The high-ash samples are more inconsistent in composition. A consideration of just the low-ash samples ensures a more uniform sample set, and thus it is more likely that the equation describing different sets of data fluctuates less.

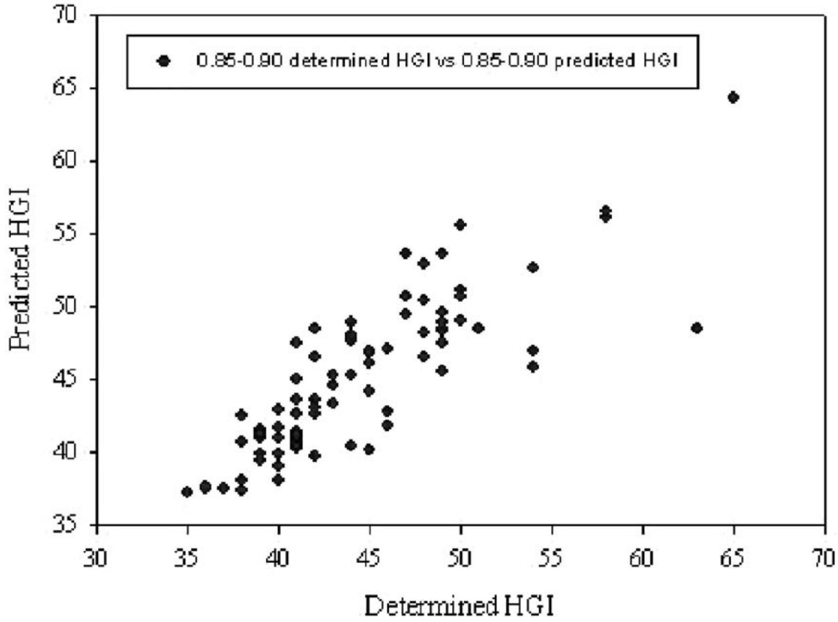

Fig. 4. Predicted vs. determined HGI for coals in the 0.85–0.90% R_{max} range.

3.4. 0.95–1.00 reflectance range

The 0.95–1.00 reflectance range consisted of 43 samples, coming from a wide array of seams (predominately, 28 of the 43, coming from Pond Creek; but also from the Darby, Harlan, Upper Harlan, Kellioka, Path Fork, Hance Zone Split No. 2, Hance Zone Split No. 3 and Hance Zone Split No. 4). The best descriptive equation of the data involved the variables ASH, exinite (EXN), VT, VL and VI, yielding an R^2 of 0.686:

$$\mathrm{HGI} = 45.378 + 0.283\ (\mathrm{ASH}) - 0.468\ (\mathrm{EXN}) + 0.147\ (\mathrm{VT}) - 1.150\ (\mathrm{VL}) + 0.310\ (\mathrm{VI}). \tag{12}$$

The 0.95–1.00 reflectance range, like the 0.85–0.90 reflectance range, discussed above, was relatively easy to fit into an equation. Despite the wide range of seams from which the samples came, there was relative uniformity in the composition of the samples. Removing the high ash samples improved the fit. Using the same variables as before and removing only two samples yielded an equation with an R^2 of 0.730:

$$\mathrm{HGI} = 40.834 + 0.334\ (\mathrm{ASH}) - 0.426\ (\mathrm{EXN}) + 0.227\ (\mathrm{VT}) - 0.640\ (\mathrm{VL}) + 0.399\ (\mathrm{VI}). \tag{13}$$

The two samples that were removed contained very high amounts of mineral matter. Once removed, the same set of variables better described the set of data. The plot of determined vs. calculated HGI values is shown on Fig. 5.

4. Conclusions

Expansion of the Hower et al. (1987) study of the relationship between Hardgrove grindability index and the microlithotype composition of coal was conducted by the addition of samples to the preciously studied reflectance ranges (0.75–0.80 R_{max} and 0.85–0.90 R_{max}) and the addition of coals from the 0.95–1.00

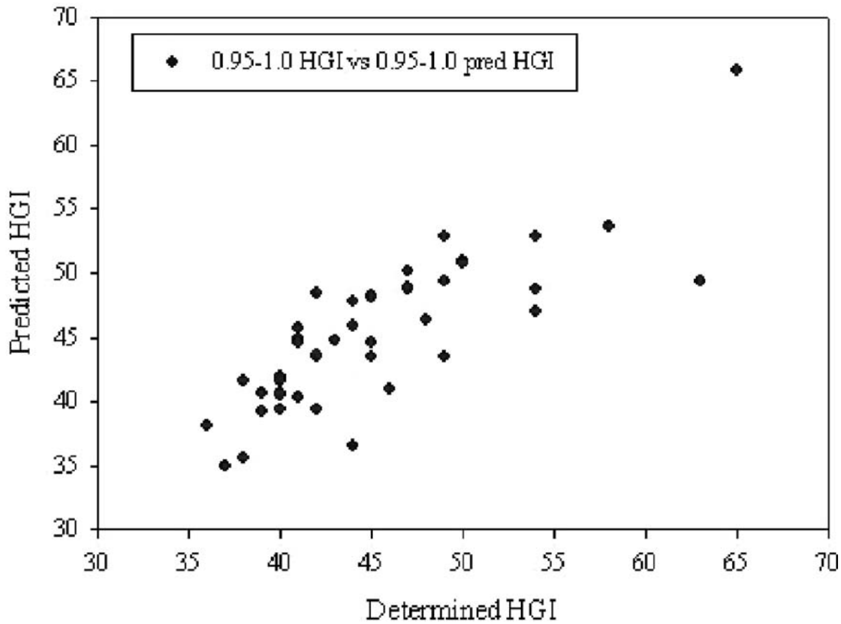

Fig. 5. Determined HGI vs. predicted HGI for eastern Kentucky coals in the 0.95–1.00% R_{max} range with ash contents less than 20%.

R_{max} to the study. In both cases, only coals from eastern Kentucky were considered.

The three reflectance ranges are not as isorank as the single-mine sets in the Hower et al. (1987) study. The following relationships were determined:

- For the 0.75–0.80 R_{max} samples with the high-ash samples removed from consideration, the monomacerite microlithotype vitrite and silicates (generally clays) had a positive contribution to HGI while the trimacerite microlithotypes duroclarite (the most abundant trimacerite in most study samples) and clarodurite had negative contributions. The ash content (by proximate analysis) also has a slight negative contribution, partially offsetting the positive contribution of the optically determined silicate fraction.
- For the 0.85–0.90 R_{max} coals with the high-ash samples removed from consideration, the bimacerite microlithotype vitrinertite has a positive contribution. Duroclarite, clarodurite, the bimacerite microlithotype durite and the monomacerite microlithotype liptite all have a negative contribution to HGI.
- For the 0.95–1.00 R_{max} coals with the high-ash samples removed from consideration, ash yield, vitrite and vitrinertite all have positive contributions to HGI. The trimacerite microlithotype vitrinertoliptite and exinite, a major component of the latter microlithotype, both have negative contributions to HGI.

Grinding properties are important in mining applications since lower-HGI (harder to grind) lithotypes will require a greater energy input (Mackowsky and Abramski, 1943; Peters et al., 1962; Hower and Lineberry, 1988). Harder, low-HGI coals are not desired by utilities due to the added time and energy required to reduce the coals to the desired size for pulverized-fuel combustion (Hower, 1998; and references therein). Both coal rank and maceral composition have an influence on grinding properties. Previous studies have indicated that maceral and microlithotype influences are more important than the rank influences. Some convergence of maceral and microlithotype properties is evident at the higher ranks, note the diminished importance of trimacerites and durite in the highest rank set, but, at least within the high volatile A bituminous rank range, macerals and maceral associations play an important role in determining HGI properties of coals. The influence does vary with rank and, therefore, HGI/maceral/microlithotype relationships established for one rank interval may not necessarily be valid for a different rank interval. Similarly, relationships established here for eastern Kentucky coals would have to be tested for similar rank coals of different provenance or age.

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