Dynamic Failure in Coal Seams: Implications of Coal Composition for Bump Susceptibility

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INTRODUCTION

Dynamic failure events in an underground coal mine, or "bumps," are defined as "the sudden, violent bursts of coal from a pillar or pillars or a block of coal, resulting in a section, the whole pillars, or the solid block of coal being thrown into an open entry" (Peng, 2008). Reports of disastrous and often fatal dynamic failure events date back over one hundred years in the United States. Mining practices and technologies have significantly evolved over the course of the last century, yet these events continue to occur. The events at Crandall Canyon, Utah (Gates et al., 2007) and Brody No. 1 Mine in West Virginia (Barker and McNeely, 2014) are two recent failure events that resulted in a total of eleven fatalities. These events testify to the fact that dynamic failure remains an imperative safety concern. Furthermore, their continued occurrences indicate that engineering controls have proven inadequate at wholly mitigating the problem.

Multiple conditions have been associated with the occurrence of dynamic failure phenomena, including

- thick, competent strata that can create a bridging effect, resulting in high abutment stresses (Rice, 1935; Holland and Thomas, 1954; Iannacchione and Zelanko, 1995; Agapito and Goodrich, 2000; Peng, 2008; Whyatt, 2008; Whyatt and Varley, 2010)
- overburden thicknesses greater than 500–700 ft. (Rice, 1935; Peng, 2008)
- a strong coal that is resistant to crushing (Rice, 1935; Peng,2008) or that is "uncleated or poorly cleated, strong… sustains high stress and tends to fail suddenly" (Agapito and Goodrich, 2000)
- the presence of sandstone channels or rolls that can serve to concentrate stresses (Iannachione and Zelanko, 1995; Agapito and Goodrich, 2000)
- fracturing of strong units above or below the coal seam (Whyatt and Varley, 2010)
- slip along pre-existing discontinuities (Peperakis, 1958; Whyatt and Varley, 2010)
- multiple seam mining interactions (Campoli, Kertis, and Goode, 1987; Iannachione and Zelanko, 1995; Newman, 2002; Peng, 2008)
- mining sequences that can cause anomalously high stress concentrations (Campoli, Kertis, and Goode, 1987; Iannachione and Zelanko, 1995)

This list represents a compilation of factors that have historically been associated with the occurrence of dynamic failure phenomena. Peng (2008) states that, "a bump may occur even though one or more…[generally accepted] geological conditions are not present." Rice (1935) suggested that a combination of factors, rather than one or two specific circumstances, is required to facilitate a bumping event. Identifying a set of conditions that will consistently produce bumping, however, has proven elusive; conditions generally associated with dynamic failure might produce an event at one site but not another. Conversely and more troubling, dynamic failure could occur where relatively few of these factors exist, although some are usually present.

In conventional coal pillar design, coal is often treated as an approximately homogenous material with a uniaxial compressive strength of 900 psi (Mark and Barton, 1997). While this practice is generally accepted, coal deposits are, in reality, heterogeneous. While treating coal as a substance that exhibits consistent material properties provides effective tools for mine design (Mark and Chase, 1997; Mark, 1999), these tools have proven ineffective at completely eradicating dynamic failure events. In fact, it could be that the differences between coal deposits hold the key to answering the question of why some coals appear to fail violently more frequently than others.

Dynamic failure events have a propensity to occur regionally or locally as indicated by the geographic clustering of bump incidences shown in Figure 1. This supposition is supported by anecdotal evidence: Peperakis (1958) describes notable cases from the Sunnyside Mine in Utah where failure events occurred during development in virgin ground, "in localities a long way from active pillar workings"—conditions not normally associated with dynamic failure phenomena. He states that these events could have been facilitated by the presence of faulting. However, faults certainly exist in other regions, yet bumps during the development phase of mining are extremely rare. This observation corroborates those of Babcock and Bickel (1984) who proposed that some coals, notably those from western coalfields, could be inherently more prone to exhibit bursting-type behavior in a laboratory environment. This suggests that some coals could be more inherently susceptible to bumping than others, creating a greater risk when coupled with the factors already known to contribute to bumping phenomena.

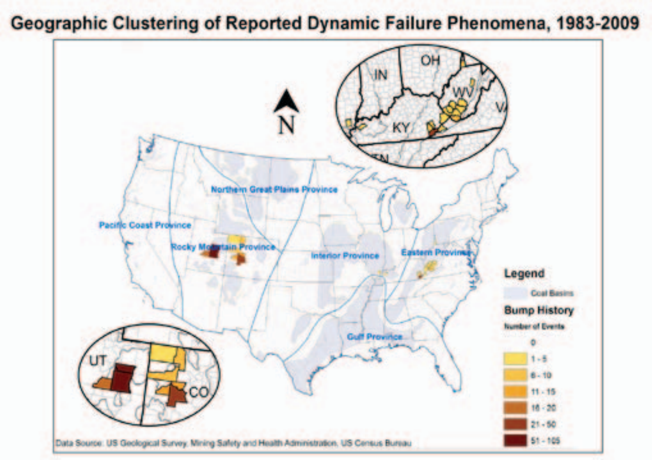

Figure 1. Regional clustering of reported bump phenomena by county, compared to coal basins.

Previous efforts to understand and model coal bumping have focused on the mechanical properties of coal (among other factors). Some of these have included unconfined compressive strength (UCS) and stiffness (Peng, 2008; Rashed and Peng, 2014; Rice, 1935; Campoli, Kertis, and Goode, 1987) as primary variables. Agapito and Goodrich (2000) indicates that cleat density could also contribute to dynamic failure in Western coal mines. While these researchers have approached the problem from different angles, it seems that the ultimate goal of these observations is to describe the capability of a coal to retain energy prior to failure and thereby resist crushing. This energy could be subsequently released kinetically, in the form of a dynamic failure event. Thus far, however, these observations have failed to yield a consistent set of physical parameters that produce bumping. Furthermore, the tests required to attain these values could be time consuming, difficult, or costly. Therefore, it would be prudent to examine other, more accessible coal attributes for correlation with bump susceptibility.

Significant success has been achieved in correlating the material properties of coals with their elemental and petrographic characteristics. Laubach, Marret, Olsen, and Scott (1998) defined an empirical relationship between vitrinite reflectance and cleat density. Van Krevelen (1961) and Van Krevelen and Schuyer (1957) describe empirical relationships between the chemical composition of coal and acoustic properties, Hardgrove Grindability Index (HGI), thermal and electric conductivity, porosity, calorific value, and other attributes. Mathews et al. (2014) provide an overview of empirically determined relationships between both elemental and petrographic parameters of coal composition and many of these physical properties. Given that coal composition directly influences the optical, physical, and material properties of coal, we hypothesize that elemental and/or moleculer variables are fundamentally linked to dynamic failure events. This concept is not without precedent; Brauner (1994) makes the observation that bumps were not observed in coals with less than 12% volatile matter. This correlation between bumping and coal composition is echoed by Osterwald, Dunrud, and Collins (1993), who stated that there is an apparent correlation between bumping and the presence of benzene in the coal matrix. This leads to the deduction that it could be possible to use coal composition to predict bump susceptibility. Were it possible to define the applicable components of coal, it would provide a more accessible and potentially more reliable measure of bump susceptibility than the commonly accepted mechanical property tests.

The Pennsylvania State University Coal Sample Bank and Database maintains an archive of bulk coal samples and a database of detailed characterizations of coal samples acquired from active or previously active mines across the continental United States. Although reliable, the wealth of information describing the elemental, petrographic, and proximate analytical character of these samples prevents simple data reduction and visualization using common data analytical procedures (e.g., scatter plots, pair-wise Pearson correlation coefficients). In the absence of a priori insight as to which measurements (variables) are correlated to bumping, an exploratory principal component analysis (PCA) provides a prudent first step.

A PCA transformation provides a convenient means of isolating only essential information contained across a large number of measurements (variables) in a manner aiding visualization and suppressing noise (Abdi, Williams, and Valentin, 2013). For example, an individual coal sample might be described by 100 distinct measurements, some of which are likely correlated, such as %volatile matter (%VM) or %Hydrogen. Using all of the available coal samples, a PCA performs a series of orthogonal projections that condense the important between-sample variance contained within the sample measurements onto a handful of new variables. Effectively, PCA estimates new axes where the similarity between each individual sample, as well as the role of each variable, is readily assessed.

In this study, a PCA was performed on 306 coal records from the Pennsylvania State Coal Sample Database to qualitatively assess a possible link between sample composition and the propensity for dynamic failure. Records include petrographic, elemental, and proximate analytical measurements and were compared to a database of dynamic failure events reported between 1983 and 2009. Associations between bump susceptibility and sample properties elucidated by PCA will allow for a more targeted use of engineering controls, foster effective risk prevention research, and ultimately lead to fewer bump related accidents and fatalities.

METHOD

Five-hundred-twenty-eight records from the Pennsylvania State University (PSU) Coal Sample Database were used for this study. Records include elemental, proximate, and petrographic analyses results from channel samples from coal basins throughout the United States. From material property data, only a subset of samples and variables were chosen to be used for a PCA due to the prevalence of missing measurements. Ultimately, 222 samples were removed from the analysis leaving 306 available for PCA. Variables such as the composition percent of vitrinite, liptinite, inertinite, carbon, nitrogen, organic sulfur, oxygen, hydrogen, volatile matter, as well as vitrinite reflectance, Btu/lb, and moisture content were used. Additional information included geographic location and seam name. While those data were not used directly in the PCA, they were key to correlating the samples with data regarding bump histories.

Using the geographic data, the 306 records were compared to an MSHA database of reported bump incidents in order to infer which samples had a higher likelihood of being "bump-positive" or "bump-negative." The database included 369 individual cases reported to the Mining Safety and Health Administration (MSHA) within the United States between 1983 and 2009. MSHA does not include information regarding the mined seam in these accident statistics. Consequently, an attempt was made to reconstruct this data for the 82 mines represented by the database, through publicly available lease information, MSHA Reports of Investigation, and state Coal Associations. These efforts were successful for 35 of these mines. The coal seams identified as having been excavated by mines with a history of dynamic failure phenomena were cross referenced with the geographic information in the list of coal records provided by the PSU Coal Sample Database. Those records correlating with a mine in which bump events had been reported were designated as bump-positive. If no association existed between a given coal record and one of these 35 mines, it was designated as bump-negative. There is some inherent error in identifying the bump status of records in this way, due to our inability to reconstruct seam information for each mine represented within the database of reported bump incidents. Some records identified as bump-negative, could, in fact, be bump-positive. Geographic data for both coal records and MSHA accident reports, however, is readily available. Given our ability to verify that bump-negative records come from counties in which no bumps were reported ensures that the magnitude of this error for this study is relatively small. Additionally, while error could exist in the identification of bump-negative seams, no such error exists in those that have been designated as bump-positive.

Initially, all available measurements were used in a PCA to determine their relative importance in defining the principal component axes. An assessment of variable importance was determined using the principal component loadings (Figure 2) where a variable was removed if (1) it was mostly uncorrelated (<0.2%) to the first 3 principal component axes or (2) if it was approximately correlated equivalently to a variable of more fundamental importance. In the latter case, for example, if a molecular-geological descriptor, such as %VM, loaded analogously to an elemental descriptor (%carbon), then %VM was removed because it is likely described fundamentally by the percent of elemental carbon contained in a coal sample. Since the number of variables was reasonably few, this heuristic approach to eliminating variables was reasonably straightforward.

Once a variable was removed, the PCA procedure repeated until the number of principal components describing the data were few (≤ 3). This procedure continued until a clear relationship between bump history or coal rank was observed on the principal component score (PC-score) plots. Variables were scaled to unit variance prior to PCA to suppress the influence of measurement unit. PCA and data visualization were performed using the Statistics Package in Matlab 2013a.

RESULTS & DISCUSSION

Figures 2 and 3 indicate an unambiguous correlation between positive bump history (Δ) and low organic sulfur content when organic sulfur (%) and volatile matter (%) are used as variables in a PCA. In other words, we see in Figure 2 that samples with a positive bump history cluster near the bottom of the base of the large triangular scatter of samples. Additionally, we see from Figure 3 that the base of the triangular point-scatter is defined by a low loading of organic sulfur, i.e., samples containing a large amount of organic sulfur content reside near the precipice of the triangular scatter whereas those with positive bump history cluster near the base of the triangular scatter. In fact, the uppermost limit of organic sulfur content within the bump-positive samples was 2.07% (Figure 2, red triangle). However, the average sulfur content for the bump-positive subset was much lower, at 0.71%. Below a threshold of approximately 2%, the number of records with a history of dynamic failure increases with decreasing sulfur content (Figure 4).

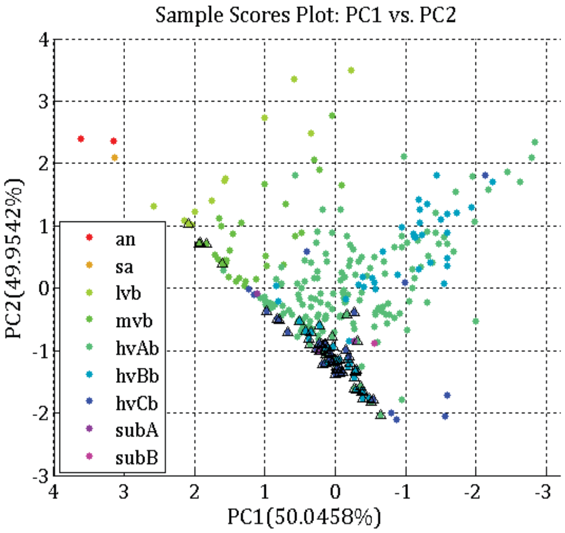

Figure 2. Results of projecting the 306 samples onto the first two principal component axes. Samples showing a positive or negative bump history are clearly marked as either triangles (Δ) or bullets (o), respectively. Supporting information in Figure 3 (below) indicate a strong correlation between sulfur content and positive bump history. Note: coal rank is color coded as anthracite (an=red), semi-anthracite (sa= yellow), low-volatile bituminous (lvb= light green), medium-volatile bituminous (mvb= green), high-volatile A bituminous (hvAb= teal), high-volatile B bituminous (hvBb= blue) , high-volatile C bituminous (hvCb= purple), and sub-anthracite (sa= pink).

Volatile matter describes the lighter hydrocarbons liberated from the coal during the combustion process. Therefore, it is important to recognize that the fraction of elemental components (hydrogen, oxygen, and carbon) roughly approximate volatile matter composition. Organic sulfur may be defined as sulfur in the coal matrix that is not a sulfate and is not pyritic in nature (Thrush, 1968). More importantly, this relationship holds regardless of location; it is true of both Eastern and Western coal mining operations. It is important to emphasize that stress-related variables pertinent to dynamic failure, such as overburden depth, mining methods, local stratigraphy, and the presence of multiple seam mining, have not been taken into account in this study. In spite of this, sulfur content appears to provide a reasonable measure of the coal's inherent capability for dynamic failure, independent of other mechanical or stratigraphic factors. To elaborate, a coal with high inherent bump-susceptibility could, in fact, never do so, if not sufficiently stressed. Coals with positive bump histories have

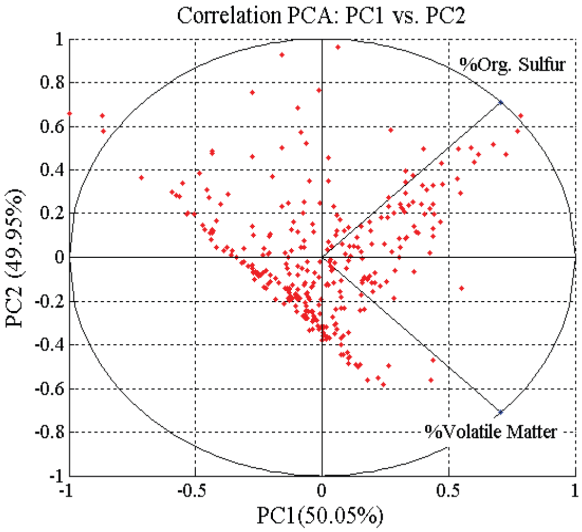

Figure 3. A principal component loadings plot indicates that high organic sulfur content and low volatile matter (%VM), approximating coal rank, are negatively correlated to bump history.

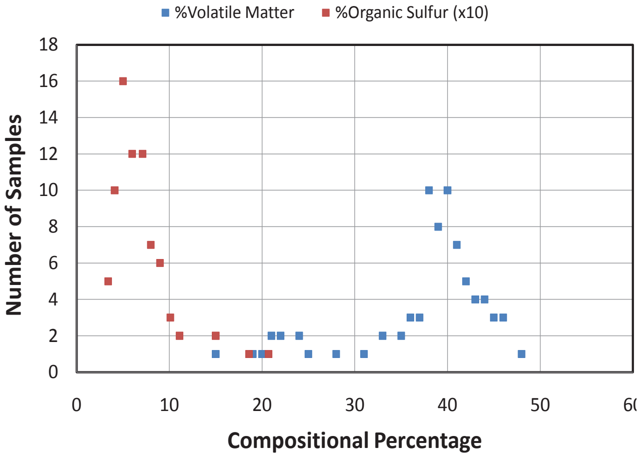

Figure 4. This graph shows the number of samples categorized as bump positive with respect to volatile matter and organic sulfur composition. Values for organic sulfur on the x axis have been multiplied by ten for ease of comparison. The apparent normal distribution of bump positive samples within a range of sulfur and volatile matter compositions suggest that there may be a range of values for both of these values most commonly associated with dynamic failure incidents.

clearly been exposed to the necessary stresses required to produce bumping; whereas, this may not be the case in the non-bumping sample subset.

PCA also revealed a linear distribution of samples on the PC-scores plot (Figure 2) according to coal rank. Figure 3 indicates that this distribution was dictated entirely by the %VM present in each sample. This behavior is unsurprising in absolute terms, considering that coal rank is defined by calorimetric methods and fixed carbon percentage that indirectly reflect the content of volatile matter present in a given sample (Schweinfurth, 2009). More importantly, coals with ranks in the low to high volatile bituminous range, show a greater fraction of total samples with a positive bump history. It is important to note that, as previously discussed, volatile matter is a convenient way to describe a combination of other elemental and molecular variables that are liberated during the combustion process. It could be that it is one of these variables specifically, rather than the overall compositional percentage of volatile matter, that is significant in these results. Further analysis is required to verify the role of volatile matter versus an isolated parameter or set of parameters within this overarching category before more confident assertions may be made as to its true role. Additionally, coal rank is a function of coal maturity, which could subsequently be associated with geologic and stratigraphic factors not accounted for in this study. It could be these factors that are contributing to the occurrence of dynamic failure phenomena, and they are being accounted for by proxy through volatile matter percentage. While the correlation between organic sulfur content and bumping is clear, it is premature at this stage of the analysis to assert an obvious connection between rank and volatile matter in understanding bump history. In that, it is entirely possible that only organic sulfur content and appropriate geological and stress conditions actually mediate the occurrence of dynamic failure.

Figure 4 illustrates the number of bump positive samples within the sample set with respect to their compositional percentages of sulfur and volatile matter. This suggests that there could be a range of values for both organic sulfur and volatile matter content within which dynamic failure events are most likely to occur. For organic sulfur composition, this range appears to be between roughly 0.40% and 0.70%. For volatile matter, this range is between roughly 38% and 41%. The ratio of volatile matter to organic sulfur (VM/S) is a convenient way to simultaneously describe the range within which a given sample will fall. Thus, it can be stated that within this sample set, a VM/S ratio between approximately 59 and 95 is associated with a higher number of bump-positive samples. It is important to note, however, that the upper limit in this range is a soft limit and could be reflective of the relative scarcity of samples with VM/S values greater than 95. In fact, there were only 9 of these, 8 of which were categorized as bump-positive. The relationship between VM/S and bump-proneness (Figure 4A), indeed, suggests that volatile-material-rich coals are more susceptible to bumping, as are sulfur-lean coals. When using the VM/S ratio, some of the outlying data points for sulfur content or volatile matter content alone are accounted for. For instance, the average sulfur content of coal in Columbia County, Pennsylvania, is extremely low at 0.56%. This is lower than the average sulfur content for bump-prone coals. However, this appears to be a non-bumping seam. This could be explained by the average volatile matter content from coal in this county, which is also extremely low at 4.51%. This and similar cases suggest that it is the combination of these which could, in fact, correlate most closely with bump positive history.

No bumps were reported in seams with a VM/S ratio of less than 24.3, based upon data from the 306 coal records. To explore whether or not this could represent a lower limit for this variable below which bumps do not tend to manifest at the stresses generated by current mining practices, the 222 coal records eliminated from the original sample set were re-introduced to the database and identified as bump-positive or bump-negative, by means of the same protocol utilized in the original 306 records. These records were then plotted by compositional percentage of volatile matter (y-axis) versus organics sulfur (x-axis). To assess

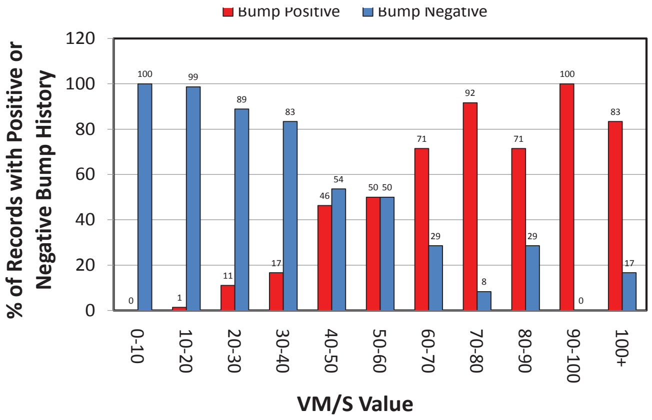

Figure 5. This graph illustrates the number of records categorized as bump-negative (blue) vs. bump-positive (red), with respect to their VM/S ratios. The graph illustrates an overall decrease in the number of bump-negative records as VM/S increases. Likewise, it illustrates an increase in the number of bump-positive records.

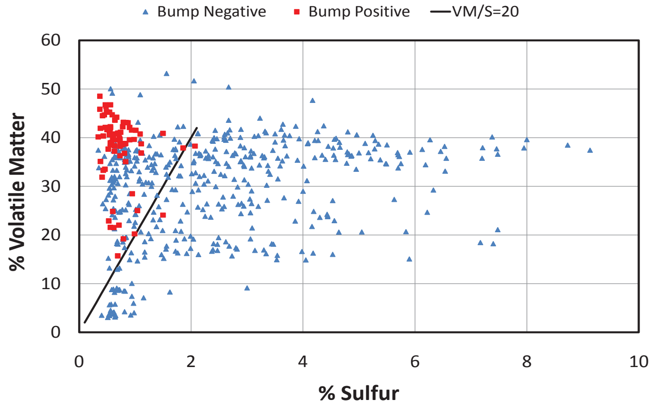

Figure 6. After re-introducing 222 previously eliminated coal records, 97.4% of bump-positive records fall above the line VM/S=20. This delineation successfully accounts for bump-negative cases with 67% accuracy.

the significance of the VM/S ratio, a line with a slope of VM/S=20 was fitted to the plotted records. Of the plotted records, 77 were categorized as bump-positive. Of these, 97.4% were well above the line VM/S=20. This discriminator was less successful at accounting for the remaining 449 bump-negative cases; only 67% of these fell below the VM/S=20 line. This could be partially accounted for by the possibility of false-negatives in the VM/S>20 range and the lack of other factors contributing to dynamic failure relevant to these cases (e.g., sufficient overburdens and stiff stratigraphy). In other words VM/S values of greater than 20 do not guarantee bumping—quite the opposite, in fact; dynamic failure events are relatively rare. However, given the presence of other factors associated with dynamic failure events, mines operating within these seams could be at significantly higher risk than are mines operating in seams with lower VM/S values. Consequently, a high VM/S ratio may be considered a necessary but insufficient criterion to facilitate dynamic failure events.

These results represent a qualitative, empirical link between the organic sulfur and volatile matter content of coals and their innate susceptibility towards dynamic failure. These results beg the issues of overburden depth, mining method, the possibility of multi-seam mining interactions, etc. It is imperative to incorporate the influences of these and other variables, and also to further explore the role of volatile matter, if a holistic picture of bumping behavior is to be constructed. Current NIOSH research seeks to create a quantitative model for prediction of dynamic failure behavior incorporating these data.

PCA-generated relationships between bump history and compositional percentages of vitrinite, liptinite, inertinite, carbon, nitrogen, and moisture have proven to be ambiguous at this time. PCA analysis revealed secondary correlations (albeit weaker) between positive bump history and higher than average nitrogen, oxygen, and hydrogen. Positive bump history was also correlated with higher than average liptinite content and lower than average vitrinite content. Some of these, such as petrographic attributes, in particular, could be correlated with other geologic influences not considered in this relatively simple study. The nature of these secondary relationships is the subject of continued investigation in order to explore their potential utility in predicting coal behavior. These relationships, however, appear to exist independently of the link between VM/S to positive bump history and, at this time, seem to be a less accurate indicator of bump susceptibility.

CONCLUSIONS

PCA analysis using coal data from the Pennsylvania Stata Coal Bank has revealed a very strong correlation between low organic sulfur content, high volatile matter, and positive bump history. The number of bump-positive samples was shown to increase with decreasing sulfur and increasing volatile matter. By taking the ratio of volatile matter to sulfur, VM/S, a minimum threshold for this value of 20 was effectively established, below which bumps are not generally induced by the stresses experienced within the sample set. This limit successfully accounts for 97.4% of bump-positive records. Samples with negative bump histories are less successfully accounted for at 67%; this highlights the fact that both inherent susceptibility and appropriate stress conditions are necessary to facilitate a dynamic failure. These results establish that one coal could, in fact, be more inherently prone to bumping than another, and this susceptibility is directly correlated to its composition. These observations further establish the necessity of addressing coals on a seam-by-seam basis in coal bump research, rather than as a homogenous material. For coal mines operated in seams with high VM/S values, the operators need to be aware of their status as potentially high-risk for bumping, and mine accordingly. This risk is inherent to the coal seam itself, independent of other variables. Understanding this facet of dynamic failure phenomena is a new piece to the puzzle, and could help to shed new light on developing a more robust model for predicting coal bumps in the future.

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