



Impact of coal density on heavy equipment efficiency in mining operations: A case study of silicified and low rank coal

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Abstract

The operational efficiency of heavy equipment in surface mining is fundamentally influenced by the physical characteristics of the extracted material. Variations in coal density, particularly the presence of highly abrasive silicified coal and low-rank (low-calorific value) coal, directly affect excavator cycle times, bucket fill factors, and machine productivity measured in tons per hour. This study addresses the challenge of quantifying how these specific material properties impact the utilization efficiency of heavy equipment (excavators) in open pit mining operation. Data collection involved direct time studies of excavator cycle times (digging, swinging, dumping, returning) across two distinct material types: highly dense, silicified coal and lower density, low-rank coal. The study found a significant inverse correlation between coal density and the efficiency metrics of heavy equipment. In this case digging time for a single pass on silicified coal increase by 183% compared to soft coal and the digging time per pass is minimal on low rank coal. For a PC1250 excavator with a 7.5 m³ bucket capacity, the elevated cycle time results in an hourly output far below that of low-rank coal. Specifically, production drops to 471 m³/hour, which is only 46% of the standard PC1250 production rate (1,018 m³/hour based on a standard cycle time of 26.5 s per pass). Conversely, Low Rank Coal with faster digging rates than silicified coal, Low rank coal achieves a shorter total cycle time per production cycle. The estimated productivity reaches 881.25 m³/hour, or 86.5% of the PC1250 standard capacity.

Keywords

Coal density, Silicified and low rank coal, Heavy equipment efficiency

Introduction

Variations in coal density, particularly the presence of highly abrasive silicified coal and low-rank (low-calorific value) coal, directly affect excavator cycle times, bucket fill factors, and machine productivity measured in tons per hour. Geological factors (such as material density and hardness) create performance gaps in heavy equipment in

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mining [1]. Silicified coal is a product of permineralization and replacement, where the original organic tissues of the plant are infiltrated and substituted by siliceous minerals, yet the macroscopic and microscopic external form (morphology) of the wood or coal precursor is perfectly preserved. Locally, silicified coals are identified by field names such as bonecoal, blackstone, or ironstone, appellations derived directly from their dark coloration and exceptional hardness. In the case of silicified coals from Tanjung Redeb, Embalut, and Loa Kulu, the material is characterized as black, highly indurated (hard), and contains dispersed fine-grained silica minerals. The silica SiO₂ content in these silicified coals ranges from 58 to 76% [2]. Silicified coal exhibits a higher density than normal coal, which can cause significant damage to mining equipment such as excavator buckets and crusher teeth when the coal enters the crushing process. Furthermore, the high ash content (or mineral matter) within the silicified coal can reduce the overall coal quality if it is co-mined with marketable coal [3]. In some cases, silicified coal possesses a hardness that severely impacts excavator production operations. For example, the compressive strength of silicified wood within the Muara Wahau Seam-1 coal layer ranges between 7,407.25 kPa until 22,487.28 kPa. Another case study indicates that silicified coal within the Muara Enin Formation in Jambi exhibits a compressive strength ranging from 15,000 kPa to 50,000 kPa, characterized by an abundance of silica and carbonaceous content [4].

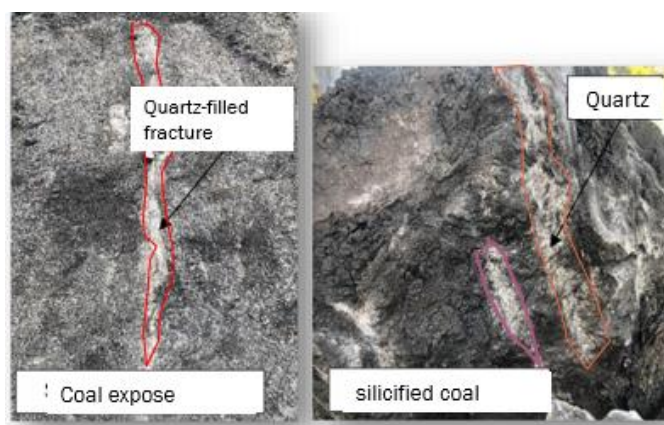
An increase in the hardness of the coal seam leads to a direct decrease in the productivity of hydraulic excavators. Harder coal restricts penetration and bucket filling, increasing cycle times. Harder, less fragmented coal significantly increases the "bucket fill time" component of the overall excavation cycle, which is a major factor in reduced efficiency [5]. Higher material densities (such as in silicified coal) require greater digging energy and affect bucket loading times [6]. This presents a serious challenge during the mining process, particularly affecting the wear and tear of excavator teeth [3]. This silicified coal is known to be the factor that can reduce the effectiveness of mining activities of its seams [7]. From the results of field observations, mapping of silicified coal in the lap and coal is very important to be done to avoid the decline in the quality of coal production [8]. The mining methodology implemented in seams containing silicified coal is a selective mining approach utilized to differentiate between the coal layer and the silicified coal layer. This operational decision consequently impacts production time and costs. While previous studies have discussed general factors in cycle time efficiency (such as road conditions and equipment performance), there is limited literature that specifically examines how variations in coal density affect this performance quantitatively. This study addresses the challenge of quantifying how these specific material properties impact the utilization efficiency of heavy equipment (excavators) in open pit mining operation. Previous studies have identified that higher material density requires greater digging energy and affects bucket loading time [6], while geological factors, such as material density and hardness, create performance gaps in heavy mining equipment. However, a knowledge gap remains, as the influence of coal density on the cycle time discrepancy between silicified coal and low-rank coal

has not been thoroughly quantified. This study aims to address this gap by providing new empirical evidence on how variations in coal density influence the bucket fill factor and cycle time dynamics within the Warukin Formation (where silicified coal is present) in South Kalimantan, against standard cycle time benchmarks.

Method

Coal samples

The methods carried out in the field are coal observation and sampling. In-situ coal sampling was performed directly at coal mining concession in South Kalimantan. The collected specimen was subsequently subjected to density determination utilizing the Archimedes principle. In situ silicified coal sample show in [Figure 1](#).



[Figure 1](#). in situ silicified coal sample

Within the study area, the silicified coal is associated with the Warukin Formation. Regionally the research area is included in the Barito Basin. The Barito Basin covers an area of 70,000 km² in Southeast Kalimantan. The Warukin Formation is a coal bearing formation in the Barito Basin. The coal in the research location has the rank of lignite to sub-bituminous coal, which is low in sulfur content. The formation of silicified coal in this unit resulted from the concentration of siliceous materials triggered by a rapid shift toward acidic pH levels in conjunction with an abundant silica supply. This process led to the deposition of silica minerals, which replaced relatively permeable wood tissues. Due to the differential permeability between the coal seams and preserved wood tissues, two distinct morphologies of silicified coal are observed in the study area: vertical and horizontal lenticular (lensing) types [\[9\]](#). In situ low rank coal sample [Figure 2](#).

The coal within the study area is characterized as low-rank, with a gross as-received (GAR) calorific value typically ranging from 4,200 to 4,400 kcal/kg. Furthermore, it exhibits favorable geochemical properties, specifically low ash content and ultra-low sulfur levels (< 0,1%). From previous research on silicified coal it was found that the result of XRD analysis shows that the seam-D containing silicified coal has clay mineral composition of 47.47% kaolinite, 21.27% illite, 23.73% smectite and 17.54% mixed layer, while the seam-E which does not contain silicified coal has a composition of kaolinite

35.78%, illite 17.88%, smectite 21.59% and mixed layer 24.76%. Kaolinite as clay mineral is believed to be the main source of the formation of silicified coal [10].



Figure 2. In situ low rank coal sample

Excavator cycle times

Data collection involved direct time studies of excavator cycle times in 1 fleet (digging, swinging, dumping, returning) across two distinct material types: highly dense, silicified coal and lower density, low-rank coal.

Cycle time data were recorded on the same day using the same loading unit, a Komatsu PC1250 excavator. The dataset comprises 52 cycle time observations for silicified coal and 85 observations for low-rank coal. Excavator cycle times (PC1250) Figure 3.

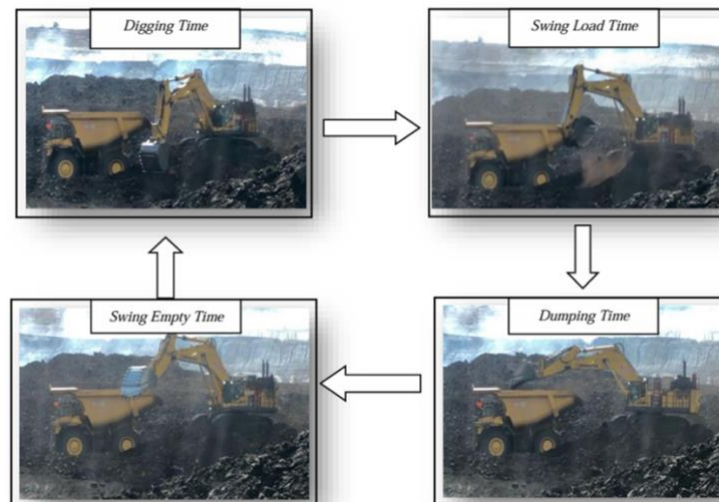


Figure 3. excavator cycle times (PC1250)

Results and discussion

Field samples were subjected to laboratory-based density testing. Simultaneously, cycle time data recorded in the field were processed to determine the mean cycle times required for subsequent analysis.

Silicified and low rank coal density

Based on the specific gravity analysis, the silicified coal exhibited a density of 1.87 g/cm³ (Table 1), whereas the low-rank coal yielded a significantly lower value of 1.22 g/cm³

(Table 2). These results indicate that the silicified coal possesses a higher specific gravity compared to the low-rank coal.

Table 1. Silicified coal density test

| No. | Parameters | Density test | | | | |
|--|------------------------------|----------------------|--------|--------|--------|--------|
| 1 | Coal type | Sub-bituminous coal | | | | |
| 2 | Method | Archimedes principle | | | | |
| 3 | Number testing | Test 1 | Test 2 | Test 3 | Test 4 | Test 5 |
| 4 | Mass (g) | 22.18 | 33.46 | 28.68 | 10.97 | 20.48 |
| 5 | Volume (cm ³) | 12.01 | 18.00 | 16.00 | 09.00 | 10.00 |
| 6 | Density (g/cm ³) | 1.84 | 1.84 | 1.78 | 1.86 | 2.04 |
| Coal density average (gr/cm ³) | | | | 1.87 | | |

Table 2. Low rank coal density test

| No. | Parameters | Density test | | | | |
|---|------------------------------|----------------------|--------|--------|--------|--------|
| 1 | Coal type | Sub-bituminous coal | | | | |
| 2 | Method | Archimedes principle | | | | |
| 3 | Number testing | Test 1 | Test 2 | Test 3 | Test 4 | Test 5 |
| 4 | Mass (g) | 21.30 | 17.59 | 12.16 | 10.97 | 16.53 |
| 5 | Volume (cm ³) | 18.00 | 14.00 | 11.00 | 09.00 | 12.00 |
| 6 | Density (g/cm ³) | 1.18 | 1.25 | 1.10 | 1.21 | 1.37 |
| Coal density average (g/cm ³) | | | | 1.22 | | |

PC 1250 cycle times

Analysis of the field cycle time measurements indicates that digging duration represents the most significant increase among the observed parameters. The excavator's digging time for silicified coal (density: 1.87 g/cm³) is substantially longer than that of low-rank coal, which possesses a lower density of 1.22 g/cm³. The recorded digging time drastically exceeds the machine's operational standards, reaching 36.81 s (representing a 183% increase over the standard digging time). Consequently, this surge in digging duration results in a significant rise in the total cycle time to 57.30 s (a 116% increase relative to the standard total cycle time). Such delays inevitably lead to a substantial reduction in the coal production efficiency of the equipment (Table 3).

Table 3. Total Cycle Time Low rank coal vs silicified coal

| Cycle times | Standard Cycle (Seconds) | Average Cycle Time (Seconds) | |
|------------------|--------------------------|------------------------------|-------------------------------|
| | | lower density, low-rank coal | highly dense, silicified coal |
| Digging | 13 | 12.27 | 36.81 |
| Swing Load | 5.5 | 5.91 | 7.34 |
| Dumping | 2.5 | 5.75 | 6.39 |
| Swing Empty | 5.5 | 6.69 | 6.74 |
| Total Cycle Time | 26.5 | 30.64 | 57.30 |

The findings of this study, which show a significant increase in digging time (silicified coal), are consistent with Demirel et al., 2018, who identified that Higher material densities (such as in silicified coal) require greater digging energy and increasing digging time.

Heavy equipment efficiency

This is a case where the material's density and hardness directly increase the digging time. Digging time represents the interval necessary for material-handling equipment, including face shovels or hydraulic excavators, to attain a maximum volumetric load in the bucket. Crucial performance indicators in this regard are Cycle Time and Loadability show in [Table 4](#).

Table 4. Loadability and estimated tonnage value low rank coal vs silicified coal

| Variation Of Coal | Loadability | Digging Time for a Single Pass (Digging Motion) | Estimated Tonnage Value Tonnage Per Pass (Capacity PC1250 : 7,5 M ³) |
|---|---|---|---|
| Silicified Coal (High Density & Hardness) | Poor Loadability category (indicating high digging resistance). | Increase by 183% compared to soft coal | Cycle time: 57.30 s 1 hours 62,8 pass Tonnage per hours : 471 m ³ /hours |
| Low Rank Coal (Low Density) | Easy loadability (the density is low, and its hardness is also low (relatively soft). | The digging time per pass is minimal | Cycle time: 30.64 s 1 hours 117.5 pass Tonnage per hours : 881.25 m ³ /hours |

The loadability of silicified coal is categorized as poor loadability, characterized by high digging resistance. Consequently, this results in a significant increase in excavation time reaching up to 183% compared to soft coal. This increase in digging time directly impacts the machine's productivity; as digging time rises, the total cycle time per pass also increases ([Table 3](#)). For a PC1250 excavator with a 7.5 m³ bucket capacity, the elevated cycle time results in an hourly output far below that of low-rank coal. Specifically, production drops to 471 m³/hour, which is only 46% of the standard PC1250 production rate (1,018 m³/hour based on a standard cycle time of 26.5 s per pass). Silicified coal is exceptionally hard due to its high silica content. This inherent hardness requires excavators or shovels to exert significantly greater penetration force and extended durations to force the bucket into the material.

Conversely, Low Rank Coal falls into the easy loadability category, meaning the digging time is relatively short due to the ease of excavation. With faster digging rates than silicified coal, Low rank coal achieves a shorter total cycle time per production cycle. The estimated productivity reaches 881.25 m³/hour, or 86.5% of the PC1250 standard capacity.

Conclusion

The material's density and hardness directly increase the digging time. Operations involving silicified coal (higher density, high abrasivity) resulted in slightly longer cycle times per cycle due to increased resistance and harder digging conditions, but yielded a higher tonnage per cycle. Conversely, low-rank coal operations demonstrated faster cycle times, but a lower tonnage per cycle due to lower bulk density, necessitating more cycles to achieve the same production target. In this case digging time for a single pass on silicified coal increase by 183% compared to soft coal and the digging time per pass is

minimal on low rank coal. For a PC1250 excavator with a 7.5 m³ bucket capacity, the elevated cycle time results in an hourly output far below that of low-rank coal. Specifically, production drops to 471 m³/hour, which is only 46% of the standard PC1250 production rate (1,018 m³/hour based on a standard cycle time of 26.5 s per pass). Conversely, Low Rank Coal with faster digging rates than silicified coal, Low rank coal achieves a shorter total cycle time per production cycle. The estimated productivity reaches 881.25 m³/hour, or 86.5% of the PC1250 standard capacity.

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