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Full Length Research Article

Impact of Weatherability on the Geomechanically Stability of Coal Pillars in Underground Mining

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Abstract

Roof stability in bord and pillar coal mines is critically influenced by the dynamic interplay of geological and operational factors. This study investigates the detrimental impact of weathering and repetitive blasting vibrations on the temporal degradation of Rock Mass Rating (RMR) and the consequent escalation of dynamic rock loads. Field investigations at operational mines were conducted to analyze these time-dependent interactions.

A modified rock load equation, incorporating time-decaying RMR, was developed. Regression analysis established empirical models correlating weathering, RMR, and increasing rock loads for standard gallery widths. The results confirm a significant temporal increase in rock load due to strength reduction from moisture, chemical weathering, and blast-induced micro-fracturing.

Conventional support systems, designed on static rock mass assumptions, are shown to be inadequate for these dynamic conditions. This research proposes integrating time-dependent factors into support design to mitigate roof fall risks. These models enable a proactive framework for stability management, facilitating timely reinforcement strategies that enhance safety and optimize resource utilization.

By addressing a primary cause of mining fatalities, this work offers actionable strategies to enhance operational safety and sustainability. The findings provide critical guidance for engineers and policymakers in developing resilient adaptive practices for underground coal mines.

Key Words- *Bord and Pillar Mining, Roof Stability, Weathering, Rock Mass Rating (RMR), Dynamic Rock Load, Support Design, Mine Safety.*

Broad Area- *Mining Engineering.*

1. Introduction and Problem Statement

Despite the long-standing practice of support installation in underground coal mines, roof falls remain a significant cause of fatalities and accidents. Conventional support design, based on static rock load calculations with a factor of safety, often proves inadequate during the mine's service life. Investigations into these failures attribute them to a complex interplay of factors, including insufficient understanding of rock mass behavior, improper support design, high induced stresses, adverse geological structures, and groundwater.

A critical oversight is the neglect of dynamic loads, which accumulate steadily on the rock mass. In unfavorable geo-mining conditions, the mechanical properties of the rock mass deteriorate over time due to mining operations, leading to a rise in dynamic load. This dynamic component differs from the static load for which the support was designed.

Consequently, a supported roof can fail without warning because the support reaction remains constant while the actual rock load increases dynamically.

1.2 CUMULATIVE DAMAGE FROM REPETITIVE BLASTING

Drilling and blasting, essential for excavation, generate stress waves and vibrations that propagate through the surrounding rock mass. These waves interact with and enlarge existing discontinuities, creating new micro-fractures. This process induces cumulative damage, a well-studied phenomenon where repeated blasting cycles cause micro-cracks to initiate, extend, and coalesce. This progressive deterioration leads to a significant reduction in the macro-mechanical properties and overall integrity of the rock mass, threatening the stability of underground structures.

1.3 TIME-DEPENDENT WEATHERING EFFECTS

Following excavation, the exposed rock surface is subjected to weathering, a time-dependent process that progressively reduces stability. Weathering, accelerated by moisture and air circulation through blast-induced fractures, causes chemical alteration and physical degradation. This weakens the rock by reducing three key parameters: Intact Rock Strength (IRS), Rock Quality Designation (RQD)/fracture frequency, and joint wall conditions.

The result is a steadily thickening weakened zone beneath the roof surface. Instability occurs once this weathered depth reaches a critical threshold, leading to shallow but recurrent failures. This cyclical process of weathering and failure must be integrated into design parameters for support systems and excavation dimensions.

1.4 Limitations of Conventional Support Design

Support systems are the backbone of underground mine stability, designed to bear strata pressure. However, their design has historically relied on initial rock mass classifications without accounting for temporal changes. Rock mass quality is dynamic, deteriorating over time due to both natural processes (weathering, stress redistribution) and anthropogenic activities (blasting, excavation geometry). This inherent limitation explains why roof falls continue to account for a substantial proportion of underground mining accidents despite adherence to guidelines.

1.5 Rock Mass Classification and the Need for a Dynamic Approach

Rock Mass Classification (RMC) systems, such as the widely used Bieniawski Rock Mass Rating (RMR) and its adaptation CMRI-RMR in India, provide a quantitative basis for characterizing rock quality and initial support design. These systems aggregate ratings from key parameters (e.g., strength, RQD, joint conditions) into a single value representing rock mass quality, which is directly correlated to a rock load equation.

However, a significant shortcoming is that these classifications represent a static snapshot in time. The core hypothesis of this work is that the RMR value itself is not constant but decays over time due to weathering. This research focuses specifically on quantifying the effect of weathering-induced RMR degradation on the ensuing increase in dynamic rock load, providing a framework for determining when additional reinforcement is required to maintain safety throughout a mine's operational life.

2. Research Objective

Following are the specific objective: -

1. To develop a time-dependent model for predicting rock load escalation in mine galleries due to weathering-induced degradation of the Rock Mass Rating (RMR).
2. To establish a methodology for the periodic assessment of rock load to enable proactive support reinforcement, thereby preventing premature roof failures.
3. To quantify the contribution of weathering to the dynamic load acting on supported roof strata.
4. To create a predictive framework for identifying the timing and location of required additional support in both galleries and junctions.

3.1 The Bord and Pillar Method and Its Challenges

the bord and pillar (b&p) method is the predominant, conventional technique for underground coal mining in india, valued for its cost-effectiveness and operational simplicity. the method involves creating a grid of interconnected galleries, leaving behind solid coal pillars for support. pillar and gallery dimensions are strictly regulated (cmr 2017, dgms) to ensure safety and economic viability.

Mining proceeds in two phases: Development (driving roadways to define pillars) and Depillaring (extracting the pillars). Both phases rely heavily on repetitive drilling and blasting operations. These repeated blasts subject the surrounding rock mass to cyclic vibrations, leading to cumulative damage and a progressive reduction in rock mass integrity over the mine's service life.

The immediate roof strata, typically composed of shales, siltstones, and sandstones, are particularly susceptible to weathering. Exposure to moisture and air, especially through blast-induced fractures, initiates chemical and physical weathering processes. This degradation directly impacts the Rock Mass Rating (RMR), a key parameter for stability assessment, implying that the designed rock load is not static but increases over time.

3.2 THE ROCK LOAD EQUATION AND ITS TIME-DEPENDENT NATURE

In Indian mines, rock load (P_r) is calculated using established empirical equations from the Paul Committee Report (1990):

For Galleries:
P_r (t/m²) = $B * D * (1.7 - 0.037 * RMR + 0.0002 * RMR^2)$

For Junctions:
P_j (t/m²) = $5 * B^{0.3} * D * (1 - RMR/100)^2$

Where:

B = Gallery width (a constant defined by regulation)
D = Density of the immediate roof rock (largely constant)
RMR = Rock Mass Rating (a variable parameter)

Support systems are designed based on this calculated P_r with a factor of safety. However, this approach assumes RMR is static. In reality, RMR degrades over time due to weathering and blast-induced damage. Since RMR is the only variable in the equation, the rock load is inherently time-dependent, increasing throughout the life of the excavation and potentially exceeding the capacity of the initial support system.

3.3 ROCK MASS CLASSIFICATION SYSTEMS

Two primary systems are used to determine RMR:

Bieniawski's RMR (B-RMR): A comprehensive system that rates six parameters: Uniaxial Compressive Strength, Rock Quality Designation (RQD), discontinuity spacing, discontinuity condition, groundwater inflow, and discontinuity orientation. The RMR value is the sum of these individual ratings.

CMRI-RMR: An adaptation of B-RMR specifically for Indian coal measures. It simplifies the system to five parameters, weighted based on statistical analysis of Indian case histories:

Layer Thickness (30% weight): The most sensitive parameter.

Structural Feature Index (25% weight): Accounts for joints, faults, and sedimentary features.

Weatherability (20% weight): Measured by the Slake Durability Index.

Rock Strength (15% weight): Determined by point load test.

Groundwater Seepage (10% weight): Measured as ml/min from a roof borehole.

The combined RMR is further adjusted using factors for depth (k1), lateral stresses (k2), induced stresses from adjacent workings (k3), and excavation method (k4), resulting in an Adjusted RMR ($RMR_{adj} = k1 * k2 * k3 * k4 * RMR$).

3.4 TIME-DEPENDENT DEGRADATION OF RMR PARAMETERS

The quality of the rock mass is dynamic, not static. Key parameters that degrade over time include:

Weatherability: Measured by the Slake Durability Index, this parameter quantifies the rock's resistance to breakdown when exposed to moisture cycles. Weathering weakens rock strength and increases fracture frequency.

Discontinuity Condition: Blast vibrations (PPV) create new micro-fractures and open existing joints. The threshold PPV a rock can withstand is directly related to its RMR; weaker rock (low RMR) is damaged by lower vibration levels.

Rock Strength: Chemical weathering and physical disintegration from wetting/drying cycles reduce the intact strength of the rock.

Structural Features: Repeated blasting can cumulatively damage the rock mass, effectively increasing the "Structural Feature Index" (a negative change) over time.

This progressive degradation means that the Adjusted RMR value at the time of excavation is a best-case scenario. The effective RMR in place will be lower months or years later, leading to a higher, dynamic rock load that was not accounted for in the original, static support design.

3.5 IMPLICATIONS FOR SUPPORT DESIGN

Conventional support design, based on a single RMR assessment, is inadequate for long-term stability. A proactive, time-dependent approach is required. This involves:

Predicting RMR Decay: Modeling the rate of RMR reduction due to weathering and blast fatigue.

Calculating Dynamic Rock Load: Using the predicted future RMR values in the rock load equation to forecast increasing load demands.

Designing Adaptive Support: Implementing support systems that can accommodate increasing loads or planning for supplementary reinforcement at predetermined times.

This methodology moves beyond static design towards a predictive maintenance strategy, crucial for preventing roof falls and enhancing safety in Bord and Pillar mines.

4.METHODOLOGY: ANALYZING THE TIME-DEPENDENT EFFECT OF WEATHERING ON RMR AND ROCK LOAD

4.1 PARAMETER SELECTION AND THEORETICAL FOUNDATION

Rock Mass Rating (RMR) systems integrate multiple geotechnical parameters. This study focuses on weatherability as the primary time-dependent variable, as other parameters (e.g., intact rock strength, layer thickness) remain largely constant over a mine's operational life. The weatherability rating (Ra), determined by the Slake Durability Index, was derived from the CMRI-RMR system. A polynomial relationship between weatherability percentage (we) and its rating was established with high correlation($R^2=0.9407$):$Ra = 0.003we^2 - 0.1442we + 1.1593$

Assuming all other RMR parameters are constant, the rate of change of RMR over time is equivalent to the rate of change of the weatherability rating :$dR/dt = dRa/dt$

Two degradation scenarios were modeled:

Uniform Rate: A constant weatherability decrease of 0.6% per 5-year interval.

Non-Uniform Rate: A variable weatherability decrease ranging from 0.5% to 1% per interval.

4.2 FIELD DATA ANALYSIS AND EMPIRICAL MODELING

Field data from the Urimari and Kedla mines (CCL) were used to model the temporal degradation of RMR and the consequent increase in rock load (RL).

Time-Dependent Relationships:
For both mines, high-correlation ($R^2 > 0.99$) polynomial equations were derived to describe:

The decrease in RMR over time ($R = f(t)$)

The decrease in weatherability over time ($we = f(t)$)

The relationship between RMR and rock load ($RL = f(R)$)

Rock Load Equations for Standard Galleries:
Using field data from multiple Indian mines, best-fit rock load equations were developed for common gallery widths, accounting for a defined density range:

For 4.2m width: $RL = 0.0028R^2 - 0.4495R + 18.822$ ($R^2 = 0.967$)

For 4.8m width: $RL = 0.003R^2 - 0.4923R + 20.828$ ($R^2 = 0.977$)

Statistical Validation: A Student's t-test confirmed no significant difference ($p\text{-value} > 0.05$) between rock loads calculated using the original CMRI formula and the new best-fit equations, validating their accuracy for predictive use.

4.3 PREDICTIVE MODELING OF DYNAMIC ROCK LOAD

The established equations were applied to predict the dynamic rock load increase over a 20-year period for several mines with 4.2m and 4.8m galleries.

Key Findings:

A uniform weatherability decrease of 0.6% per 5 years resulted in a consistent and measurable increase in rock load over time across all studied mines.

For example, in a typical mine with a 4.2m gallery, the rock load increased by approximately 0.11 t/m² over 20 years. In a mine with a 4.8m gallery and lower initial RMR, the increase was more pronounced, at nearly 0.21 t/m².

This demonstrates that the rock load is not static but is a dynamic parameter that increases progressively due to weathering.

5. RESULTS AND ANALYSIS

This study established empirical relationships to quantify the impact of weathering-induced RMR degradation on dynamic rock load in bord and pillar coal mines. The analysis, conducted using least squares regression, followed a systematic, five-step approach:

Step 1: Weatherability-Rating Relationship A high-fidelity polynomial function ($R^2 = 0.9407$) was derived to define the rating value (Ra) assigned to a measured Slake Durability Index (we) within the RMR framework: $Ra = 0.003we^2 - 0.1442we + 1.1593$

Step 2: RMR-Weatherability Correlation Strong correlations ($R^2 \geq 0.99$) were found between the overall RMR value and weatherability for both uniform and non-uniform weathering scenarios at the case study mines (Urimari and Kedla), confirming weatherability as a primary driver of RMR change.

Step 3: Time-Dependent Degradation Models High-correlation models ($R^2 \geq 0.99$) were developed to predict the decline in both weatherability (we) and RMR over a 20-year period. These models provide a predictive tool for estimating the rate of rock mass quality deterioration.

Step 4: Dynamic Rock Load Estimation The time-decaying RMR values were incorporated into rock load equations. The results demonstrate a clear, quantifiable increase in rock load (RL) over time, modeled with high confidence ($R^2 \geq 0.9898$). This confirms that rock load is not static but a dynamic parameter that escalates as the rock mass weathers.

Step 5: Generalized Rock Load Equations for Design

To extend the applicability of the findings, generalized rock load equations were developed for the two most common gallery widths in Indian mines, validated against field data from multiple sites:

For 4.2m width: $RL = 0.0028R^2 - 0.4495R + 18.822$

For 4.8m width: $RL = 0.003R^2 - 0.4923R + 20.828$

Key Graphical Results: The analysis for both gallery widths (4.2m and 4.8m) yielded consistent graphical trends:

Figure 1 & 3: Plotting rock load against weatherability shows a negative correlation; as weatherability decreases (rock degrades), the calculated rock load increases.

1. For 4.2m gallery width

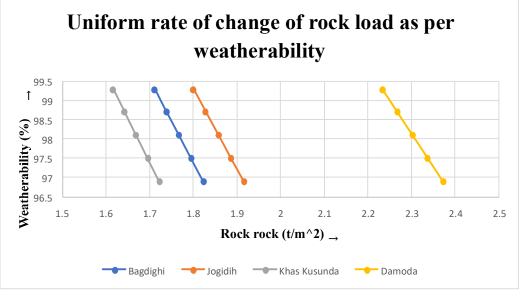

Fig. no. 1 A graph of Weatherability-Rock load for 4.2m gallery width

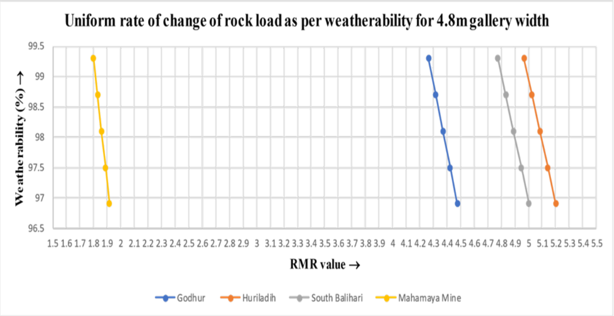

Fig. no. 3 A graph of uniform rate of change of rock load wrt weatherability for 4.8m gallery width

Figure 2 & 4: Plotting rock load against time reveals a positive, non-linear trend. This visually confirms the central finding: rock load progressively increases over the mine's service life due to weathering, even when all operational parameters remain constant.

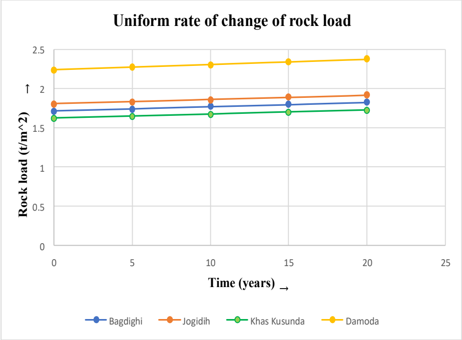

Fig. no. 2 A graph of uniform rate of change of rock load wrt time for 4.2m gallery width

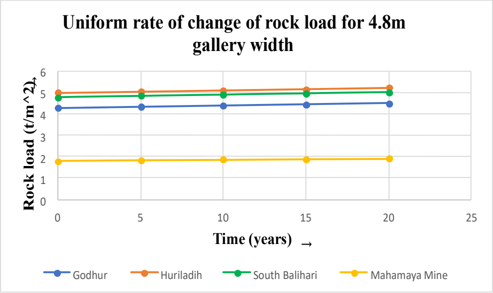

Fig. no. 4 A graph of uniform rate of change of rock load wrt time for 4.8m gallery width.

6. Conclusion

This Research Successfully Transitions From A Static To A Dynamic Paradigm For Assessing Roof Stability. By Focusing On Weatherability As A Key Time-Dependent Variable, The Study Provides A Method To: Predict the rate of RMR degradation.

Forecast the corresponding increase in imposed rock load.

Generalize these predictions for standard mine geometries using validated equations.

The findings underscore the critical inadequacy of conventional support design based on an initial, single-point RMR assessment. The demonstrated increase in rock load over time signifies that supports may become under-designed years after installation, leading to potential instability.

7. Practical Implications

This study successfully quantifies the time-dependent degradation of rock mass properties due to weathering and its direct impact on roof stability. By integrating: A weathering-dependent RMR model, Empirical rock load equations for standard galleries, and Predictive regression analysis, a robust framework for forecasting dynamic rock load is presented. The findings underscore the critical limitation of conventional support design based on a single, initial RMR assessment. Practical Recommendation: Mining engineers should adopt a proactive, time-dependent support design strategy. This involves using predictive models to forecast increases in rock load and planning for supplemental reinforcement or designing supports with adequate capacity to handle these future loads, thereby significantly enhancing long-term roof stability and preventing ground control failures.

Practical Implication: A proactive maintenance strategy, informed by predictive models of dynamic rock load, is essential for enhancing long-term safety in underground coal mines. This methodology facilitates the strategic design of focused support interventions, leading to more efficient use of materials and the prevention of roof collapse events.

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