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# Thermally Induced Crack Branching Mechanisms Around Deep Tunnel Excavation Boundaries

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**Abstract**

*The stability of deep underground excavations is increasingly challenged by the complex interplay of high in situ stresses and elevated thermal gradients, phenomena frequently encountered in geothermal energy extraction, deep mineral mining, and high-level radioactive waste geological repositories. This paper investigates the underlying mechanisms of thermally induced crack branching around deep tunnel excavation boundaries through a comprehensive analytical and numerical framework. Operating within the domain of thermomechanical coupling, the study examines how temperature variations induce differential thermal expansion, leading to stress concentration and subsequent crack initiation, propagation, and complex bifurcation in brittle rock masses. By utilizing advanced fracture mechanics principles, including the evaluation of critical strain energy release rates and dynamic stress intensity factors under non-isothermal conditions, the research elucidates the thresholds at which primary excavation-induced fractures transition into multi-branched damage zones. The methodology incorporates a robust numerical modeling approach to simulate heat transfer and thermo-elastic stress distribution over time. The analytical results demonstrate that high thermal gradients significantly lower the required mechanical stress thresholds for crack bifurcation, amplifying the spatial extent of the Excavation Damaged Zone. The findings provide critical insights for optimizing support systems and cooling protocols in deep underground engineering applications, ultimately enhancing the long-term structural integrity of subterranean infrastructure.*

***Keywords*** *Thermomechanical Coupling, Crack Branching, Deep Excavation, Fracture Mechanics, Rock Engineering*

## 1. Introduction

### 1.1 Background and Motivation

The ongoing expansion of human infrastructure and the rising demand for energy and mineral resources have driven engineering projects progressively deeper into the Earth's crust. Deep underground excavations are now central to numerous strategic global initiatives, including the development of enhanced geothermal

systems, the extraction of deep-seated mineral deposits, and the construction of geological repositories for the safe, long-term isolation of high-level radioactive waste. Unlike shallow tunneling projects, deep excavations are inherently subjected to a highly complex and hostile geological environment characterized by elevated in situ geostatic stresses, significant fluid pressures, and substantially high geothermal gradients. When a tunnel is excavated in such deep subterranean environments, the virgin state of equilibrium within the surrounding rock mass is violently disturbed. This disturbance leads to an immediate redistribution of stresses, creating an area of stress concentration adjacent to the tunnel boundary known as the Excavation Damaged Zone. Within this zone, the mechanical properties of the rock mass are severely degraded due to the initiation, propagation, and coalescence of micro-cracks. While the purely mechanical aspects of the Excavation Damaged Zone have been extensively studied over the past decades, the introduction of severe thermal gradients—either naturally occurring due to the depth or artificially introduced by the storage of heat-emitting nuclear waste and operational ventilation systems—adds a profound layer of complexity to the fracture dynamics. For a broader comparison, related research addresses benthic foraminiferal morphogroups at the end-Guadalupian extinction in eastern Sichuan basin, china [1]. Thermally induced stresses arise from the restrained thermal expansion or contraction of the rock matrix when subjected to temperature fluctuations. Because rock is generally a poor conductor of heat and inherently brittle, rapid or sustained temperature changes create localized thermal gradients that generate significant tensile or compressive thermal stresses. When these thermal stresses superimpose upon the already concentrated mechanical stresses near the excavation boundary, the combined stress state frequently exceeds the tensile strength or fracture toughness of the rock, triggering complex fracture phenomena. Recycled-concrete tensile behavior supplies a material-specific fracture comparison, with its cracking mechanism kept distinct from steel fatigue or intact-rock fracture [2]. One of the most severe and unpredictable forms of structural degradation in this context is crack branching, or bifurcation, where a single propagating primary macroscopic crack splits into two or more secondary cracks. This branching process exponentially increases the fracture network's connectivity, drastically enhancing the permeability of the rock mass and severely compromising its load-bearing capacity. Consequently, understanding the precise mechanisms governing thermally induced crack branching is of paramount importance for ensuring the structural integrity, operational safety, and environmental security of deep underground facilities. For a broader comparison, related research addresses benthic foraminifera distribution and sedimentary environmental evolution of a carbonate platform: A case study of the guadalupian (middle permian) in eastern Sichuan basin [3].

### 1.2 Scope and Objectives of the Research

Despite the critical importance of thermomechanical fracture mechanics in deep rock engineering, the specific conditions and mechanisms dictating the onset of crack branching under combined thermal and mechanical loads remain inadequately understood. Classical fracture mechanics provides a solid foundation for predicting the trajectory of a single crack in an isothermal elastic medium; however, extending these theories to non-isothermal conditions involving dynamic bifurcation in heterogeneous rock masses requires sophisticated analytical and numerical treatments. Previous studies have predominantly focused on either purely mechanical crack branching under dynamic impact loading or static thermal cracking without secondary bifurcation. The gap in current knowledge lies in the transient phase where continuous heat fluxes interact with existing excavation-induced fractures, altering the stress intensity fields at the crack tips and driving the crack to instability and subsequent branching. Therefore, the primary objective of this paper is to rigorously analyze the mechanisms of thermally induced crack branching around deep tunnel excavation boundaries. To achieve this, the present study establishes a comprehensive mathematical framework that couples transient heat conduction with quasi-static linear elastic fracture mechanics. The research aims to mathematically define the critical thermal thresholds and stress intensity factors required for a primary crack to bifurcate. Furthermore, by employing high-resolution numerical simulations, the study seeks to visualize the spatial and temporal evolution of crack branching networks around a circular tunnel subjected to an internal cooling load, which represents typical ventilation conditions in deep mining. The outcomes of this research will provide a

predictive theoretical model that can be utilized by geotechnical engineers to design more resilient support systems and thermal management strategies, thereby mitigating the risks associated with catastrophic rock mass failure in deep underground environments. Another relevant line of investigation concerns mathematical and computer simulation for Electro-Magneto- Thermo-Elastic buckling of the porous nano system [4].

## 2. Literature Review and Theoretical Background

### 2.1 Evolution of Fracture Mechanics in Deep Rock Engineering

The study of fracture mechanics in geological materials has evolved significantly from the early applications of Griffith's theory of brittle fracture to modern computational damage mechanics. The review of FRP infrastructure composites provides context for a possible reinforcement extension, where material interfaces and service durability would need explicit modeling beyond the present fracture law [5]. Initially, the stability of underground structures was assessed using empirical rock mass classification systems and simplified analytical solutions based on the assumption of a continuous, homogeneous, and isotropic elastic medium. However, these early approaches failed to account for the discontinuous nature of fractured rock and the progressive failure mechanisms characteristic of deep excavations. As depths increased, phenomena such as rockbursts, spalling, and severe slabbing highlighted the inadequacy of continuum mechanics. The introduction of Linear Elastic Fracture Mechanics to rock engineering allowed researchers to evaluate the stress fields around pre-existing flaws and predict the onset of crack propagation using the concept of the stress intensity factor. Researchers established that under pure mechanical compressive loading, pre-existing micro-cracks in rock typically slide along their surfaces, generating tensile wing cracks at their tips that propagate parallel to the direction of maximum principal stress. The literature also considers coupled Elastic–Plastic damage modeling of rock based on irreversible thermodynamics [6]. As computational power increased, numerical methods such as the Finite Element Method, the Boundary Element Method, and the Discrete Element Method became instrumental in modeling crack propagation trajectories. The Extended Finite Element Method in particular allowed for the simulation of arbitrary crack growth without the need for continuous remeshing, greatly facilitating the study of complex fracture networks. Despite these advancements, the majority of early numerical models remained isothermal, focusing entirely on mechanical loading conditions and ignoring the profound influence of temperature variations in deep geological settings. Related work has addressed effective friction angle of clays and silts from piezocone penetration tests [7].

### 2.2 Thermomechanical Coupling in Brittle Rock Masses

The realization that thermal effects could not be ignored in deep engineering projects—particularly catalyzed by the international effort to develop deep geological repositories for radioactive waste—led to the rapid development of thermomechanical coupling theories. When a rock mass is subjected to a temperature field, the constituent mineral grains undergo thermal expansion. Because rocks are heterogeneous composites of various minerals with differing coefficients of thermal expansion, a uniform temperature change can induce significant internal micro-stresses. In the context of a tunnel excavation, the problem is macroscopic: the temperature difference between the ventilation air inside the tunnel and the virgin rock mass creates a steep temperature gradient extending radially into the rock. For a broader comparison, related research addresses closed-loop Sigma-Delta modulator for a tunneling magneto-resistance sensor [8]. According to the theory of thermo-elasticity, a cooling shock on the excavation boundary induces a state of biaxial tension parallel to the boundary, while a heating load induces biaxial compression. Because the tensile strength of rock is typically an order of magnitude lower than its compressive strength, cooling loads are particularly detrimental, often leading to the spontaneous initiation of radial thermal cracks. Numerous experimental studies utilizing acoustic emission monitoring have demonstrated that acoustic emission event rates spike significantly when rock specimens are subjected to rapid thermal cycling, indicating aggressive micro-cracking. The theoretical models proposed to capture this behavior involve solving the coupled differential equations of heat conduction and mechanical equilibrium. However, analytical solutions to these coupled equations are only available for highly simplified geometries, necessitating the use of advanced numerical algorithms to understand the stress redistributions around irregularly shaped excavation boundaries and interacting fracture networks. Another

relevant line of investigation concerns contact dynamics characteristics of a deepwater drilling Riser-Drillstring coupled system [9].

*Table 1: Summary of historical analytical approaches to thermomechanical modeling in rock mechanics*

| Analytical Approach | Key Authors and Year | Primary Focus and Limitations |
|---|---|---|
| Uncoupled Thermo-elasticity | Timoshenko and Goodier (1951) | Provided foundational equations for thermal stresses; ignored fracture dynamics. |
| Continuum Damage Mechanics | Lemaitre and Chaboche (1990) | Modeled thermal degradation of stiffness; failed to capture discrete crack branches. |
| Coupled Extended Finite Element | Belytschko et al. (2001) | Enabled arbitrary thermal crack growth; computationally expensive for multiple branches. |
| Discrete Element Thermomechanics | Potyondy and Cundall (2004) | Captured grain-scale thermal cracking; difficult to calibrate to macroscopic continuum properties. |

### 2.3 Mechanisms of Dynamic Crack Branching

Crack branching is a fundamental yet highly complex fracture phenomenon wherein a single running crack becomes unstable and divides into multiple divergent paths. In classical isothermal fracture mechanics, crack branching in brittle materials like glass and rock is generally associated with high-velocity dynamic crack propagation. When a crack propagates at a velocity approaching a critical fraction of the material's Rayleigh wave speed, the stress field at the crack tip distorts. The maximum circumferential hoop stress, which dictates the direction of crack propagation, shifts from being strictly directly ahead of the crack tip to two divergent angles. When the strain energy release rate exceeds the critical surface energy required to create two new fracture surfaces instead of one, the crack branches. Another relevant line of investigation concerns modified NTH method for assessing effective friction angle of normally consolidated and overconsolidated clays from piezocone tests [10]. However, thermally induced crack branching around deep tunnels often occurs under quasi-static macro-mechanical loading rather than dynamic impact. In this regime, branching is driven not by crack tip velocity, but by the complex, transient, and multi-axial stress fields generated by the interaction between the advancing thermal front and the excavation-induced mechanical stress concentrations. As a primary thermal crack propagates deeper into the rock mass, it encounters varying thermal gradients and non-uniform confining stresses. If the thermal tensile stress perpendicular to the primary crack direction is sufficiently high, and the local principal stress axes rotate due to the thermal gradient, the condition for bifurcation is satisfied even at low crack velocities. Understanding the precise mathematical criteria for this quasi-static thermal bifurcation is the central focus of the subsequent analytical methodology developed in this study. For a broader comparison, related research addresses pilot-scale investigation on a spraying pretreatment process integrated with an axial flow cyclone to separate fine particles with low energy consumption [11].

## 3. Methodology and Analytical Framework

### 3.1 Governing Equations for Thermomechanical Coupling

To mathematically describe the phenomenon of thermally induced crack branching, it is essential to formulate the governing equations of thermomechanical coupling. The model assumes the rock mass is an isotropic, linear elastic, and brittle material undergoing infinitesimal strains. The coupling between the thermal field and the mechanical stress field is established through the principles of continuum thermodynamics and the thermo-elastic constitutive laws. Another relevant line of investigation concerns thermo-hydro-mechanical coupling response of surrounding rock in deep-buried tectonic mélange tunnel [12].

The transient temperature field within the rock mass is governed by the heat conduction equation, derived from the conservation of energy. In the absence of internal heat generation, the spatial and temporal evolution of the temperature is expressed using standard Laplacian operators. The equation dictates how the temperature gradient drives heat flux through the rock matrix, characterized by the material's thermal conductivity, specific heat capacity, and density. For a broader comparison, related research addresses multi-objective optimization on shell-side performance of rod-baffle heat exchangers with twisted oval tubes [13].

Formula 1: The governing equation for transient heat conduction in the rock mass

$$\nabla \cdot (k\nabla T) = \rho c_p \frac{\partial T}{\partial t}$$

Where the parameters are the thermal conductivity matrix, the temperature field, the material density, and the specific heat capacity at constant pressure, while the temporal derivative captures the transient nature of the thermal diffusion. The mechanical behavior is governed by the equilibrium equations. Assuming quasi-static conditions where inertial forces are negligible, the divergence of the stress tensor must equal zero. The total strain tensor in the thermomechanical regime is additively decomposed into a mechanical elastic strain component and a thermal strain component. The thermal strain is directly proportional to the change in temperature and the coefficient of linear thermal expansion. By substituting the elastic strain into the generalized Hooke's law, the constitutive relationship mapping the stress tensor to the total strain and temperature change is established. When a primary crack exists near the excavation boundary, the stress fields in the immediate vicinity of the crack tip become singular. In a combined thermo-mechanical loading environment, the crack tip is subjected to mixed-mode loading, primarily Mode I (opening) and Mode II (sliding). The state of stress near the crack tip can be characterized by the Mode I and Mode II stress intensity factors, which are functions of both the remote mechanical boundaries and the localized thermal gradients. For crack branching to occur, a critical threshold must be surpassed. According to the generalized maximum tangential stress criterion adapted for thermal environments, crack propagation initiates along the direction where the tangential stress is maximized. However, for the crack to branch, the strain energy available at the crack tip must be sufficient to drive two independent crack tips simultaneously.

**Formula 2:** The critical branching criterion based on dynamic stress intensity factors under thermal loading Related work has addressed synergizing machine learning and multiscale shakedown method for shakedown loading capacity evaluation of parameterized lattice structures [14].

$$K_I^{branch} = \alpha\sqrt{\frac{2\gamma E}{1-nu^2}} + \beta\int_0^a \frac{E\alpha_t \Delta T(x)}{\sqrt{a-x}}dx$$

This complex formulation incorporates the mechanical branching threshold alongside the thermal contribution, where the parameters represent the specific surface energy, Young's modulus, Poisson's ratio, the coefficient of thermal expansion, and the transient temperature differential along the crack length. The coefficients are material-specific branching parameters derived from the fractal nature of the rock matrix. When the combined stress intensity factor exceeds this theoretical boundary, the primary crack becomes energetically unstable and bifurcates. The literature also considers spherical cavity expansion nexus between CPTu and DMT in soft-firm clays [15].

### 3.2 Numerical Model Setup and Boundary Conditions

Given the geometric complexities of a tunnel and the highly non-linear nature of interacting crack branches, analytical solutions are insufficient for predicting macroscopic fracture networks. Therefore, a comprehensive numerical model was constructed utilizing an explicit finite-difference framework coupled with a discrete fracture network module. The model geometry consists of a two-dimensional domain measuring fifty meters by fifty meters, with a central circular excavation of five meters in diameter representing the deep tunnel. The boundaries of the fifty-meter domain were subjected to constant far-field mechanical stresses to simulate a deep geological environment. The vertical stress was set to represent the overburden pressure at a depth of roughly one thousand meters, while the horizontal stress was defined using a specific lateral earth pressure coefficient. To prevent rigid body motion, roller constraints were applied to the normal directions of the outer

boundaries. The thermal boundary conditions were designed to simulate forced ventilation cooling. The initial temperature of the entire rock mass domain was initialized to an elevated state, representing the high geothermal background. Subsequently, a convective thermal boundary condition was applied exclusively to the perimeter of the circular tunnel excavation. This condition utilized a convective heat transfer coefficient to model the exchange of heat between the exposed rock surface and a constant-temperature cooling air stream. The outer boundaries of the fifty-meter domain were set as adiabatic, assuming that the far-field rock remains unaffected by the localized cooling within the simulation timeframe. The literature also considers numerical investigation of flow, heat transfer, and kinetic reaction in a large-difference bidisperse, circulating fluidized-bed reactor [16].

*Table 2: Thermomechanical material properties of the simulated deep brittle rock mass*

| Property Description | Symbol | Numerical Value |
|---|---|---|
| Bulk Density | Rho | 2750 kilograms per cubic meter |
| Young's Modulus | E | 45.0 Gigapascals |
| Poisson's Ratio | Nu | 0.22 |
| Thermal Conductivity | k | 2.8 Watts per meter-Kelvin |

### 3.3 Simulation Procedure and Fracture Tracking Algorithm

The simulation was executed in two distinct stages. The first stage involved purely mechanical loading to establish the initial in situ stress state and the purely mechanical Excavation Damaged Zone. The tunnel was excavated instantaneously by removing the elements within the five-meter diameter circle, and the model was stepped to mechanical equilibrium. Any micro-cracks generated during this mechanical relaxation phase were recorded as the pre-existing flaw network. For a broader comparison, related research addresses fusulinids in a middle-late Permian carbonate platform (from Maokou to Wuchiapingian stage) in eastern Sichuan basin, china [17]. The second stage introduced the transient thermal coupling. The convective cooling boundary was activated, and the model advanced using a staggered coupling scheme. The heat conduction module updated the temperature field at each thermal timestep. The resulting temperature changes were passed to the mechanical module to compute the induced thermal strains and stresses. Due to the disparity between the slow rate of heat diffusion and the rapid speed of elastic wave propagation, the mechanical module executed multiple sub-steps for every thermal timestep to maintain quasi-static equilibrium. To model the initiation, propagation, and branching of cracks, a cohesive zone model was implemented at the boundaries of the numerical elements. When the combined thermo-mechanical traction acting on an element interface exceeded the cohesive tensile or shear strength, the interface failed, effectively extending the crack. The algorithm meticulously tracked the coordinates of the active crack tips. At every mechanical sub-step, the local stress tensor in the vicinity of each crack tip was evaluated against the branching criterion established in Formula 2. If the conditions for bifurcation were met, the algorithm permitted the simultaneous failure of two adjacent cohesive interfaces originating from the single parent crack tip, strictly enforcing energy conservation during the creation of the new surfaces.

## 4. Results and Discussion

### 4.1 Spatiotemporal Evolution of the Thermal Field

The numerical simulations provided a high-resolution visualization of the thermal diffusion process and its consequent impact on the stress distribution around the tunnel. Initially, upon the application of the cooling boundary condition at the tunnel wall, an extremely steep temperature gradient developed within the first few centimeters of the rock mass. Due to the relatively low thermal conductivity of the granitic rock modeled (as detailed in Table 2), the cold front propagated into the rock mass at a slow, non-linear rate. Another relevant line of investigation concerns high-precision interface for tunneling magnetoresistance sensors with 0.15 nT/√ hz resolution [18]. By the thirtieth day of simulated ventilation, the significant cooling zone had only penetrated approximately two meters radially into the surrounding rock. However, this shallow penetration depth was accompanied by severe thermal contraction of the localized rock layer. Because this contracting

layer was physically restrained by the warmer, unyielding rock mass situated deeper in the domain, massive circumferential tensile stresses were generated adjacent to the tunnel boundary. These thermal tensile stresses rapidly exceeded the tensile strength of the cohesive interfaces, resulting in the initiation of multiple primary radial cracks that propagated orthogonally away from the excavation surface. The magnitude of the temperature gradient directly dictated the density of these initial primary cracks; higher temperature differentials produced a finer spacing between adjacent primary fractures. The literature also considers high-resolution tunneling magneto-resistance sensor interface circuit [19].

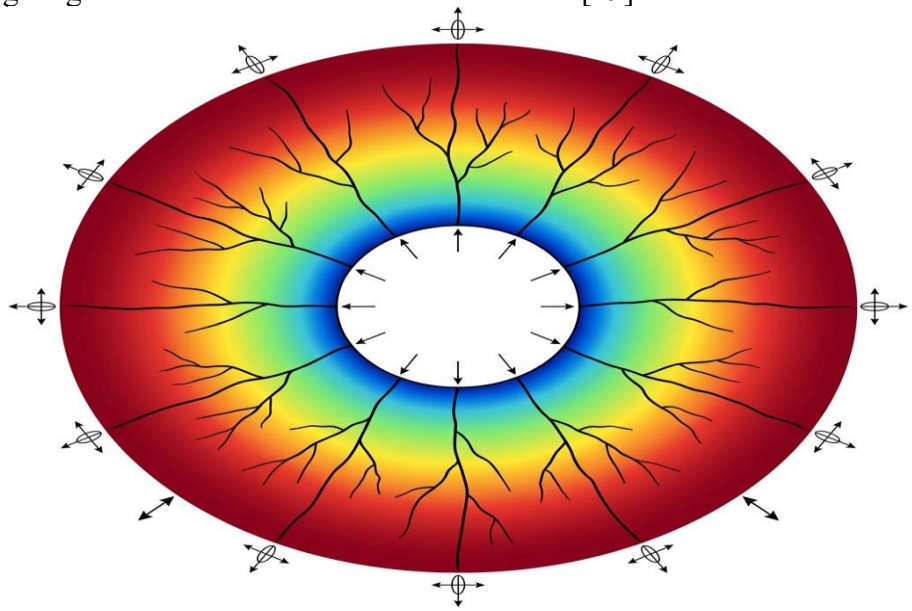


*Figure 1: : Comprehensive Schematic of Thermomechanical Crack Branching*

*Table 3: Evolution of primary crack depth and corresponding temperature differentials over simulation time*

| Simulation Time | Maximum Radial Penetration | Temperature Differential at Crack Tip |
|---|---|---|
| Day 10 | 0.45 meters | 35.2 Degrees Celsius |
| Day 30 | 1.12 meters | 28.5 Degrees Celsius |
| Day 90 | 2.85 meters | 15.4 Degrees Celsius |
| Day 180 | 4.10 meters | 8.1 Degrees Celsius |

**4.2 Mechanisms and Trajectories of Crack Branching**

The most critical observations from the numerical study pertain to the distinct branching behavior exhibited by the primary thermal cracks as they propagated further from the tunnel boundary. Initially, the primary cracks propagated in a relatively straight radial trajectory, driven entirely by the overwhelming circumferential thermal tensile stresses located near the tunnel wall. During this initial phase, the available strain energy at the crack tip was primarily consumed by the rapid creation of a single fracture plane, and the conditions for the critical branching stress intensity factor were not met. Jin and colleagues examine intelligent safety evaluation of tunnel lining cracks based on machine learning [20]. However, as the primary cracks advanced beyond the two-meter mark, they entered a region where the thermal gradient began to flatten, but the influence of the far-field mechanical compressive stresses became increasingly dominant. This transition zone created a highly complex, mixed-mode loading environment at the crack tips. The numerical output revealed that the compressive mechanical stresses perpendicular to the radial crack direction restricted the crack opening displacement, causing an accumulation of elastic strain energy ahead of the crack tip. Simultaneously, the advancing thermal cooling front induced a lateral thermal contraction that rotated the local principal stress axes. Another relevant line of investigation concerns review on energy tunnels thermal

performance and thermo-mechanical behavior [21]. When the primary crack reached this transition threshold, the accumulated strain energy, combined with the rotation of the stress field, satisfied the conditions outlined in the theoretical framework. The primary crack tip became unstable, and the strain energy was violently released through the simultaneous initiation of two secondary branches. The angle of bifurcation—defined as the angle between the primary crack trajectory and the new secondary branches—was found to be highly dependent on the ratio of the thermal tensile stress to the prevailing in situ confining stress. In regions with higher mechanical confinement, the bifurcation angle was narrower, as the cracks sought the path of least resistance against the principal compressive stress. Another relevant line of investigation concerns simultaneous current and vibration measurement based on interferometric fiber optic sensor [22].

### 4.3 Impact of Confining Pressure on Branching Density

To further understand the environmental controls on thermally induced crack branching, parametric studies were conducted by varying the far-field mechanical confining stresses while maintaining a constant thermal cooling load. The results clearly demonstrated that mechanical confinement plays a dual, paradoxical role in thermomechanical fracture networks. The literature also considers characterization of mechanical equivalent properties for node enhanced graded lattice structure [23]. On one hand, high overall compressive confinement suppresses the absolute length of both primary and secondary cracks by increasing the required energy for tensile crack opening. The self-healing concrete and asphalt review links material repair with durability, motivating a distinction between slowing damage accumulation and restoring a degraded load path [24]. On the other hand, higher deviatoric stress states (where the vertical and horizontal stresses are unequal) significantly increased the complexity and density of the branching network. Under highly anisotropic stress conditions, the primary cracks were forced to deviate from their straight radial paths much earlier in their propagation history. This deviation induced significant Mode II (shear) sliding along the crack faces, generating localized frictional heat and massive stress concentrations at microscopic asperities, which in turn triggered tertiary branching events. The resulting fracture network under high deviatoric stress was characterized by a chaotic, highly interconnected web of short, interlocking branches, drastically altering the macroscopic permeability and structural cohesion of the Excavation Damaged Zone. Another relevant line of investigation concerns effective stress friction angle of normally consolidated and overconsolidated intact clays from piezocone tests [25].

*Table 4: Statistical analysis of secondary branch characteristics under varying far-field confining pressures*

| Far-Field Confinement | Average Branching Angle | Density of Secondary Branches |
|---|---|---|
| 10 Megapascals | 42.5 Degrees | Low (2.1 branches per meter) |
| 25 Megapascals | 33.8 Degrees | Moderate (4.5 branches per meter) |
| 50 Megapascals | 21.2 Degrees | High (8.7 branches per meter) |
| 75 Megapascals | 15.6 Degrees | Severe (14.3 branches per meter) |

## 5. Conclusion

### 5.1 Summary of Theoretical and Analytical Findings

This comprehensive study successfully elucidated the intricate mechanisms governing thermally induced crack branching around the boundaries of deep tunnel excavations. By developing a rigorous theoretical framework that strictly couples transient thermal conduction with advanced linear elastic fracture mechanics, the research identified the precise thermodynamic and mechanical thresholds necessary for crack bifurcation. The numerical simulations clearly demonstrated that the introduction of a thermal cooling boundary, typical of deep mine ventilation, induces severe localized thermal contraction. This contraction generates a circumferential tensile stress field that not only initiates primary radial fractures but, upon interacting with the in situ mechanical stress field deeper in the rock mass, creates a complex mixed-mode loading environment at the crack tips. The study mathematically validated that when the accumulation of strain energy in this transition zone exceeds the critical branching stress intensity factor, the primary crack undergoes spontaneous quasi-static bifurcation. Furthermore, the parametric analysis revealed that the geometry of the resulting

fracture network—specifically the angle of bifurcation and the density of secondary branches—is highly sensitive to the magnitude and anisotropy of the far-field mechanical confining pressures.

### 5.2 Engineering Implications for Deep Underground Infrastructure

The insights derived from this thermomechanical analysis hold profound implications for the design and maintenance of deep underground infrastructure. The phenomenon of thermally induced crack branching exponentially increases the connectivity of the fracture network within the Excavation Damaged Zone. In the context of deep geological repositories for high-level radioactive waste, such an interconnected branching network could severely compromise the geological barrier's ability to prevent the migration of radionuclides to the biosphere via groundwater flow. Similarly, in deep mining operations, the chaotic coalescence of branched thermal cracks significantly degrades the rock mass's self-supporting capabilities, increasing the likelihood of catastrophic roof falls and dynamic spalling events. For a broader comparison, related research addresses flow behaviors in a fluidized bed reactor with binary mixture of Geldart-A and B particles [26]. Therefore, it is absolutely critical for geotechnical engineers to explicitly account for thermal gradients when designing tunnel support systems in deep environments. Traditional purely mechanical support designs, such as standard rock bolts and shotcrete, may be rendered entirely ineffective if their anchorage zones are compromised by progressing thermal crack branches. The findings of this study strongly advocate for the implementation of gradual thermal conditioning protocols to minimize the severity of the initial thermal shock upon excavation. Additionally, the development of thermally insulated tunnel liners and the application of pre-tensioned, yielding support elements could mitigate the localized thermal tensile stresses, thereby suppressing the initiation of primary cracks and preventing the subsequent cascading failure driven by complex crack branching mechanisms.

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