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Research on the Geochemical Kinetics and Intelligent Control of Heavy Metal Pollution in Acid Mine Drainage

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Acid mine drainage (AMD) represents one of the most severe environmental challenges in abandoned mining areas of China. Its formation and evolution are controlled by coupled geological-hydrological-microbial factors, exhibiting significant spatiotemporal heterogeneity and complex kinetic processes. This paper systematically reviews the geochemical kinetic mechanisms of heavy metal pollution in AMD and proposes a scientific framework encompassing the entire "source-pathway-receptor" process. Research reveals that pyrite oxidation is controlled by parallel pathways involving O_2(aq) and Fe^{3+}, with their coupling increasing acid production rates by 30%-50%. Carbonate media achieve removal rates of 99.82%, 100%, and 94.47% for TFe, Al^{3+}, and As^{5+}, respectively, but show limited effectiveness for Mn^{2+} and Cd^{2+} (<50%), revealing mineral-phase-controlled mechanisms for multi-metal synergistic removal. In dispersed alkaline matrix systems, removal rates for Al, Fe, and Zn reach 98.58%, 51.51%, and 35.45%, respectively, with precipitate mineral assemblages including schwertmannite, goethite, and alunite. Based on integrating the "multi-field coupling-intelligent regulation-synergistic remediation" theoretical framework proposed by Zhang Fawang‘s team, this paper constructs an AMD prevention and control technology system covering “mechanism analysis-technology development-engineering application”. It proposes a “digital twin + intelligent sensing” precision control platform and a “water-soil-biota” synergistic remediation paradigm, providing scientific support for ecological environment management in abandoned mining areas of China.