ICJK

Journal of Advanced Materials Research
http://dx.doi.org/10.62762/JAMR.2025.621965

PERSPECTIVE

Check for updates

# Shaping the Future of Underground Monitoring with Carbon-fiber Self-sensing Smart Materials

**Shan Ning**[1], **Xing Gao**[1], **Weibing Zhu**[1], **Jiaxing Ding**[1], **Guang Xu**[2] **and Jingmin Xu**[2,*]

[1] School of Mines, China University of Mining and Technology, Xuzhou 221116, China
[2] Department of Mining Engineering, Missouri University of Science and Technology, Rolla, MO 65401, United States

## Abstract

**Amid global warming, energy shortages, and the increasing frequency of extreme climate events, the development of sustainable and intelligent underground infrastructure has become a critical strategy for addressing major societal challenges. Unlike surface structures, underground infrastructures are subjected to high stress, dynamic loading, and groundwater erosion. Under such conditions, traditional cement-based materials are prone to strength degradation, fatigue damage, and permeability failure, which significantly limits the service life and operational safety of underground constructions. Incorporating short carbon fibers into cement-based materials not only enhances their mechanical strength but also enables real-time monitoring of internal stress, deformation, and damage states through changes in the electrical resistivity of the carbon fiber network. The application of this material in underground engineering leverages its dual functions of structural reinforcement and damage monitoring, realizing the concept of "material as a sensor." However, several challenges remain in the practical application of this material. First, groundwater erosion may affect the stability of the mechanical and damage monitoring performance of carbon fiber composites. Second, the reliability of its damage monitoring performance under long-term high-stress environments has yet to be verified. Additionally, large-scale engineering applications must also consider the economic feasibility of the material. Conducting in-depth research in these areas will vigorously promote the large-scale application of carbon fiber composites in high-stress and water-bearing underground environments, providing key technical support for the long-term safe operation of engineering structures.**

**Keywords**: smart materials, self-sensing composites, underground engineering monitoring, carbon-fiber reinforcement.

## 1 Introduction

With the intensification of infrastructure construction and the deepening of resource exploitation, the demands on the mechanical properties of underground engineering materials and structural stability are gradually elevated. Representative mega-projects such as the Sichuan–Tibet Railway,

**Submitted:** 19 November 2025
**Accepted:** 18 December 2025
**Published:** 15 January 2026

**Vol.** 2, **No.** 1, 2026.
10.62762/JAMR.2025.621965

***Corresponding author:**
Jingmin Xu
jingmin.xu@hotmail.com

**Citation**
Ning, S., Gao, X., Zhu, W., Ding, J., Xu, G., & Xu, J. (2026). Shaping the Future of Underground Monitoring with Carbon-fiber Self-sensing Smart Materials. *Journal of Advanced Materials Research*, 2(1), 1–7.

where the maximum overburden reaches 2 080 m, and the Jinping-II Hydropower Station, whose maximum burial depth attains 2 525 m, are both situated within complex geological settings at kilometer-scale depths [1, 2]. Moreover, it was reported that the extraction depth of South African gold mines has already extended to 4 000 m [4]. Compared with surface structures, underground engineering has to not only sustain high stress, but is also frequently subjected to dynamic loading and groundwater infiltration. Under such conditions, conventional cement-based materials are prone to strength deterioration, fatigue damage and seepage-induced failure, which severely restrict the service life and operational safety of underground works [1, 6]. Currently, the stability of underground structures is typically monitored using localized point sensors, such as rock-bolt and borehole stress meters [7–9]. By collecting parameters like stress and deformation in the monitored zone, the stability of the coal mass is judged. However, the monitoring range of such sensors is limited; a single device cannot cover the entire structure or tunnel section [10]. Micro-seismic monitoring can capture rock-mass fracturing signals over a larger volume [11–13]. However, it is susceptible to false signals and misinterpretation caused by blasting and other anthropogenic activities. Although distributed fiber optic sensing technology has made breakthroughs in spatial resolution, it is still limited by issues such as the complex coupling between the optical fiber and matrix material, the high difficulty of data analysis, as well as problems like fragility and difficulty in noise elimination under harsh environmental conditions [14].

Carbon fiber composites possess the characteristic of "material as a sensor," enabling real-time monitoring of the internal stress state, crack propagation, and health status of structures through the resistance changes in the conductive network. Developing new underground-engineering materials that simultaneously possess high mechanical performance and long-term durability, together with the capability for real-time structural damage monitoring, has therefore become a critical scientific challenge and an urgent technical demand for guaranteeing safe, efficient and sustainable underground construction. Against this background, carbon-fiber-reinforced cement-based composites, by virtue of their unique property advantages, exhibit enormous application potential.

## 2 Performance Advantages of Carbon Fiber Composites

The potential of carbon fiber composites originates from their excellent high strength [15] and unique self-sensing damage characteristics, which have made them a focus of research in the field of engineering materials. Composed mainly of carbon, carbon fibers exhibit high temperature resistance, wear resistance, thermal conductivity, and corrosion resistance, along with high strength and elastic modulus along the fiber axis. In engineering applications, the diameter of carbon fibers generally ranges between 5-7 micrometers, while their length is controlled between 6-12 millimeters based on engineering requirements. During the preparation process, methods such as ultrasonic dispersion and the use of dispersing agents are typically employed to ensure the uniform distribution of fibers within the matrix.

Carbon fiber composites can significantly enhance the mechanical strength and toughness of cement-based materials. By uniformly dispersing high-strength short carbon fibers in the cement matrix, the bridging effect of the fibers markedly enhances mechanical performance. Research indicates that adding 1%, 2%, and 3% by volume of carbon fibers to the cement matrix can increase its flexural strength by 72%, 95%, and 138%, respectively [16]. Since carbon fiber possesses extremely high tensile strength (typically 5-10 times that of steel), it can effectively transfer tensile stress across crack surfaces, inhibiting further crack opening and propagation. This bridging action disperses a single macroscopic crack into multiple micro-cracks, thereby significantly improving the material's flexural strength, tensile strength, and fracture toughness.

Damage self-sensing represents the most unique feature of carbon fiber composites. Carbon fibers are intrinsically highly conductive. When its content in the cement matrix reaches a certain critical value (the percolation threshold), the initially isolated carbon fibers begin to connect with each other, forming a continuous three-dimensional conductive network that permeates the entire material. At this point, the macroscopic electrical resistivity of the material decreases by several orders of magnitude, transitioning from an insulator (or semiconductor) to a conductor. However, the initiation, growth, and propagation of microcracks within the material can compromise these fiber connections, leading to breakage and disruption of the conductive network. This damage to the network structure is irreversible and leads to a significant increase in the material's macroscopic electrical resistivity. The more developed the internal cracks are, the greater the degree of damage to the conductive network, and the larger the magnitude of the resistivity increase. Hence, by monitoring changes in electrical resistivity, it is possible to accurately determine the initiation, accumulation, and interconnection of internal damage within the structure, enabling the monitoring of the entire process from micro-damage to macro-failure. By virtue of this characteristic, carbon fiber composites have been widely applied in the fields of bridges, construction, and aerospace [17–19].

## 3 Application Potential of Carbon Fiber Composites in Underground Engineering

The application of carbon fiber composites in underground engineering represents a crucial step in advancing traditional support structures towards intelligence and functionalization (Figure 1). Its core advantage lies in achieving "structure-function integration", which combines load-bearing support and damage monitoring functions within a single material. This means that support structures made of carbon fiber composites act not merely as passive components resisting external loads, but also as a large-scale, distributed, and active sensing network capable of autonomously monitoring their own health status and responding to environmental changes.

In conventional underground engineering applications, the use of carbon fiber composites can not only effectively enhance the load-bearing capacity of support structures but also meet the requirements for structural stability monitoring [20]. For instance, constructing permanent support with carbon fiber composites along the periphery of an underground tunnel can directly enhance the strength and toughness of the support structure due to their excellent mechanical properties, thereby improving the structure's compressive and flexural resistance [3]. Simultaneously, the material's inherent self-sensing damage capability enables real-time, continuous monitoring of the internal stress state, crack initiation, and propagation within the support structure. This provides crucial data for engineers to assess the structural health condition, facilitating proactive early warning.

Furthermore, leveraging the sensitivity of carbon fiber composites' electrical resistivity to changes in moisture content can address the long-standing water seepage challenges in underground engineering [20]. In projects such as underground reservoir dams or tunnels passing through aquifers, water infiltration poses a significant threat to structural stability and safety. When external moisture penetrates carbon fiber composite structures, it markedly alters the resistivity of the monitored areas. By deploying a monitoring network [21], it is possible not only to assess the structural stress state and stability but also to accurately identify the formation, progression, and spatial location of groundwater seepage pathways. These application scenarios fully demonstrate the advantages of this material's "structure-function integration", enabling engineers and technicians to evaluate structural stability based on real-time monitoring data. However, translating this application into practical engineering requires resolving the multiple challenges it may encounter in complex underground environments.

## 4 Challenges and Potential Solutions

Unlike surface structures, underground engineering works are often exposed to highly humid or directly water-immersed environments. Therefore, the influence of water on the mechanical properties and damage monitoring stability of carbon fiber composites must be fully considered [20]. Specifically, water influences the material in two primary ways [21]. Firstly, water molecules and erosive ions in water (such as $SO_4^{2-}$ and $Cl^-$) can degrade the interfacial bonding strength between the carbon fibers and the cement matrix, consequently weakening the fiber bridging effect. Secondly, water-soluble ions can affect the electrical conductivity of the material, causing changes in electrical resistance even when no damage has occurred. This can mask the resistance changes caused by material damage [5], thereby interfering with the stability of the self-sensing signal. To address this issue, potential solutions include applying waterproof coatings to the material surface or developing new types of carbon fiber composites with hydrophobic characteristics to enhance their stability in damp or water-bearing environments.

Another critical issue is the reliability of damage monitoring performance under long-term high-stress conditions. Existing research has predominantly focused on laboratory uniaxial compression tests and cyclic loading tests. Regarding the long-term high-stress conditions commonly encountered in underground engineering, studies on the evolution of the mechanical and monitoring properties of carbon fiber composites remain relatively scarce. During

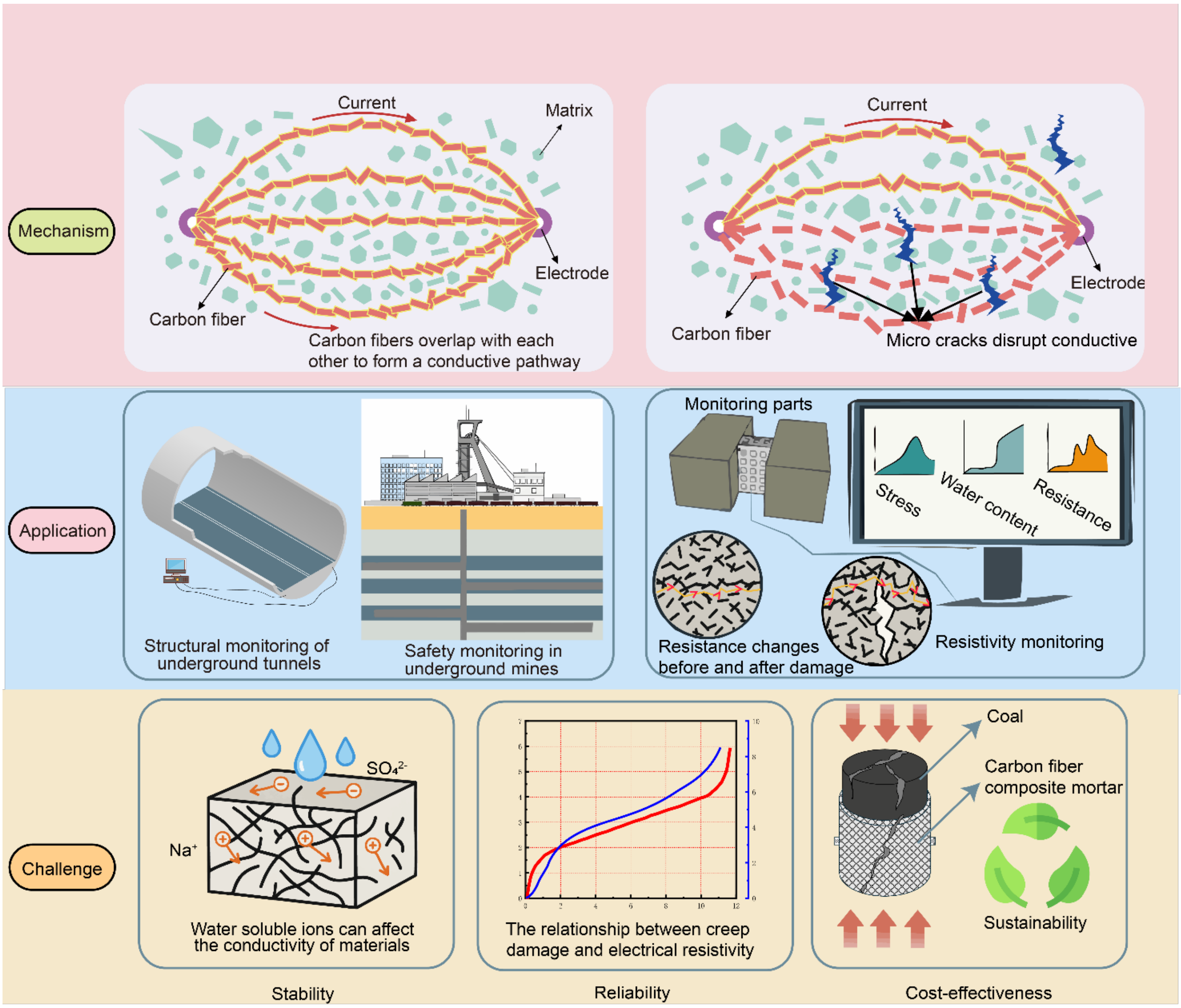


**Figure 1.** Application of carbon fiber composites in underground engineering.

long-term loading processes, the bonding strength at the interface between carbon fibers and the matrix, the accumulation process of micro-damage, and the corresponding patterns of electrical resistance change associated with material creep damage are still not well understood. For instance, does creep damage under high stress lead to a continuous and gradual change in electrical resistivity? How can the resistance change caused by creep be effectively distinguished from signals indicating sudden damage? Resolving these questions is essential for ensuring the long-term reliability of damage monitoring using carbon fiber composites. If this mapping relationship cannot be clarified, the monitoring system will face an extremely high false alarm rate. Therefore, the introduction of deep learning and other artificial intelligence algorithms for in-depth feature extraction and pattern recognition of complex signals is the viable solution to address the issue of noise and damage signal overlap, and to enhance the reliability of long-term monitoring data [22].

Furthermore, the relatively high cost of carbon fiber necessitates careful consideration of economic feasibility for large-scale applications. Although the price of carbon fiber has decreased in recent years, it remains significantly higher compared to traditional bulk building materials like cement and steel. In projects involving tunnels several kilometers long or large-scale underground cavern complexes, the comprehensive use of carbon fiber composites would lead to a substantial increase in project costs, making it economically unfeasible. A viable strategy is to adopt a "zonal application" approach, where carbon fiber composites are prioritized for use in critical sections rather than being uniformly distributed throughout the entire structure. For instance, in tunnel support systems, carbon fiber composites can be applied to the lining surface or within stress concentration zones, enabling precise monitoring of stress and damage in these key areas. This application method not only significantly reduces material usage and project costs but also ensures accurate monitoring of the mechanical and damage states in the most critical and vulnerable sections of the structure. It is particularly suitable for large-scale underground projects with limited budgets.

## 5 Conclusions and Prospects

Carbon fiber composites, leveraging their excellent mechanical properties and unique damage self-sensing functionality, provide an innovative solution for enhancing the safety monitoring of deep underground engineering. By integrating load-bearing and sensing functions into a single material, they enable real-time, distributed monitoring of structural stress states, damage evolution, and seepage pathways. However, challenges remain regarding the long-term performance stability of these composites in water-rich and high-stress environments, the reliability of the damage-electrical resistance response mechanism, and the associated costs. Future research should focus on the long-term performance evolution of carbon fiber composites under water-rich and high-stress conditions and on developing low-cost application technologies. Breakthroughs in these key areas will be pivotal for enabling the widespread application of this material in challenging underground environments characterized by high stress and high humidity, thereby providing a solid guarantee for the long-term safe operation and maintenance of engineering structures.

## Data Availability Statement

Data will be made available on request.

## Funding

This work was supported by the National Natural Science Foundation of China under Grant 52478389.

## Conflicts of Interest

The authors declare no conflicts of interest.

## AI Use Statement

The authors declare that no generative AI was used in the preparation of this manuscript.

## Ethical Approval and Consent to Participate

Not applicable.

## References

[1] Yang, Z., Zhang, R., Ai, T., Lv, Y., Zhang, Z., Xie, J., & ... (2024). Triaxial failure behavior and microfracture source time–frequency characteristics of marble under in situ stress conditions at different depths considering engineering disturbance. *Measurement*, *237*, 115274. [CrossRef]

[2] Xue, Y., Kong, F., Yang, W., Qiu, D., Su, M., Fu, K., & ... (2020). Main unfavorable geological conditions and engineering geological problems along Sichuan-Tibet railway. *Chinese Journal of Rock Mechanics and Engineering*, *39*(3), 445–468. [CrossRef]

[3] Xu, J., Gao, M., Wang, Y., Yu, Z., Zhao, J., & DeJong, M. J. (2025). Numerical investigation of the effects of separated footings on tunnel-soil-structure interaction. *Journal of Geotechnical and Geoenvironmental Engineering*, *151*(7), 04025057. [CrossRef]

[4] Sithole, S. M., van Laar, J. H., Gous, A. G. S., & Schutte, C. S. L. (2025). A constructive method to improve mine tertiary cooling systems planning and efficiency evaluation. *Applied Thermal Engineering*, *279*, 127768. [CrossRef]

[5] Gao, G., & Meguid, M. A. (2022). Microscale characterization of fracture growth in increasingly jointed rock samples. *Rock Mechanics and Rock Engineering*, *55*(10), 6033–6061. [CrossRef]

[6] Liu, Z., Zhang, Y., Liu, G., Wang, Y., Yu, W., & Jiang, J. (2025). Damage evolution of UHPC under coupled high stress, temperature, and osmotic pressure: New multi-field experiment and non-destructive techniques. *Powder Technology*, *455*, 120793. [CrossRef]

[7] Singh, A. K., Ram, S., Kumar, A., Waclawik, P., & Kukutsch, R. (2024). Stability study of coal pillars due to induced stress-driven spalling during development and mechanised depillaring at different depths of cover. *Canadian Geotechnical Journal*, *62*, 1-16. [CrossRef]

[8] Gao, G., Meguid, M. A., & Zhang, L. (2024). Exploring the role of sample size on fracture growth mechanisms in intact rock: insights from 3D DEM-DFN analysis. *Canadian Geotechnical Journal*, *62*(1), 1–24. [CrossRef]

[9] Shen, B., Duan, Y., Luo, X., Werken, M. V. D., Dlamini, B., Chen, L., & ... (2020). Monitoring and modelling stress state near major geological structures in an underground coal mine for coal burst assessment.

*International Journal of Rock Mechanics and Mining Sciences, 129*, 104294. [CrossRef]

[10] Mngadi, S. B., Durrheim, R. J., Manzi, M. S. D., Ogasawara, H., Yabe, Y., Yilmaz, H., & ... (2019). Integration of underground mapping, petrology, and high-resolution microseismicity analysis to characterise weak geotechnical zones in deep South African gold mines. *International Journal of Rock Mechanics and Mining Sciences, 114*, 79–91. [CrossRef]

[11] Xu, W., Ma, C., Li, T., Shi, S., Peng, F., Chen, Z., & ... (2025). Dynamic interpretation of stress adjustment types in high geostress hard rock tunnels based on microseismic monitoring. *International Journal of Mining Science and Technology, 35*(4), 801–816. [CrossRef]

[12] Duan, Y., Luo, X., Si, G., & Canbulat, I. (2022). Seismic source location using the shortest path method based on boundary discretisation scheme for microseismic monitoring in underground mines. *International Journal of Rock Mechanics and Mining Sciences, 149*, 104982. [CrossRef]

[13] Khanal, M., Shen, B., Duan, Y., & Luo, X. (2023). Application of seismic sensors on measurement while drilling for real-time rock property detection. In *IOP Conference Series: Earth and Environmental Science* (Vol. 1124, No. 1, p. 012096). IOP Publishing. [CrossRef]

[14] Zhou, G., & Sim, L. (2002). Damage detection and assessment in fibre-reinforced composite structures with embedded fibre optic sensors - review. *Smart Materials and Structures, 11*(6), 925–939. [CrossRef]

[15] Han, B., Zhang, K., Yu, X., Kwon, E., & Ou, J. (2012). Electrical characteristics and pressure-sensitive response measurements of carboxyl MWNT/cement composites. *Cement and Concrete Composites, 34*(6), 794-800. [CrossRef]

[16] Toutanji, H. A., El-Korchi, T., & Katz, R. N. (1994). Strength and reliability of carbon-fiber-reinforced cement composites. *Cement and Concrete Composites, 16*(1), 15–21. [CrossRef]

[17] Dardar, S., Eamon, C. D., & Parra-Montesinos, G. (2024). Flexural reliability of CFRP-strengthened bridge girders. *Journal of Performance of Constructed Facilities, 38*(1), 04023065. [CrossRef]

[18] Panda, P. N., Chakrabarti, A., & Prakash, V. (2024). Theoretical study of self-balancing pretensioned CFRP cable braces for seismic resistance of buildings. Journal of Composites for Construction, 28(4), 04024029. [CrossRef]

[19] Teti, R., Segreto, T., Caggiano, A., & Nele, L. (2020). Smart multi-sensor monitoring in drilling of CFRP/CFRP composite material stacks for aerospace assembly applications. *Applied Sciences, 10*(3), 758. [CrossRef]

[20] Zhao, B., Ning, S., Xu, J., Li, T., Luo, W., Gao, P., & Zhu, W. (2025). A Carbon Fiber-Reinforced Backfill Composite with Self-Sensing Capability for Mine Stability Monitoring. *Rock Mechanics and Rock Engineering, 58*(11), 12737-12754. [CrossRef]

[21] Zhou, Z., Xie, N., Cheng, X., Feng, L., Hou, P., Huang, S., & Zhou, Z. (2020). Electrical properties of low dosage carbon nanofiber/cement composite: Percolation behavior and polarization effect. *Cement and Concrete Composites, 109*, 103539. [CrossRef]

[22] Vujović, I., Šoda, J., & Golub Medvešek, I. (2025). Review of Trends in Wavelets with Possible Maritime Applications. *Signals, 6*(4), 70. [CrossRef]

**Shan Ning** received the PhD. degree in mining engineering from China University of Mining and Technology, in 2023. His research focuses on smart materials and intelligent monitoring. (Email: shan.ning@cumt.edu.cn)

**Xing Gao** received the B.S. degree in mining engineering from China University of Mining and Technology, in 2024. (Email: ts24020012a31ld@cumt.edu.cn)

**Weibing Zhu** received the PhD. degree in mining engineering from China University of Mining and Technology, in 2010. He is now a full professor at China University of Mining and Technology. (Email: zweibing@163.com)

**Jiaxing Ding** received the B.E. degree in mining engineering from China University of Mining and Technology, in 2024. He is now a master student at China University of Mining and Technology. (Email: ts24020008a31ld@cumt.edu.cn)

**Guang Xu** received the PhD. degree in mining engineering from Virginia Tech, VA 24061 USA, in 2013. His research focuses on advancing safety and environmental standards in mining operations through innovative material design, experimental optimization, simulation, and AI modeling. He is now an Associate Professor at Missouri University of Science and Technology, USA. (Email: guang.xu@mst.edu)

**Jingmin Xu** received the PhD. degree in civil engineering from the University of Nottingham, UK, in 2020. His research interests include smart materials and intelligent monitoring. He served as an Editorial Board member for the Journal of Advanced Materials Research, and Scientific Reports. (Email: jingmin.xu@hotmail.com)