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***Research paper***

# Study on Mechanical Properties of Waste Gangue-Based Backfill Material for TBM Lining in Coal Mines

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**Abstract**

This study prepares backfill material for TBM segment lining using waste gangue as coarse aggregate combined with cement mixed slurry. The research explores the variation in uniaxial compressive strength under three curing periods (1d, 7d, 14d) with different water-cement ratios and admixture proportions. Results show that waste gangue-modified bean gravel as coarse aggregate extends the compaction stage, imparts good ductility, and significantly improves compressive strength. Compressive strength increases steadily with extended curing time. When admixtures are added in specific proportions, they effectively enhance early strength and further increase peak compressive strength, achieving early strength and high strength effects. After mixing with slurry, waste gangue forms an interactive reinforcement effect through three key processes: gangue interlocking, bonding reinforcement, and cementation solidification. During material compaction, the stress-strain curve sequentially undergoes three stages: pore compaction, slip adjustment, and fracture reconstruction.

***Keywords***: *Waste Gangue; Solid Waste Backfilling; Compressive Strength; Backfill Material; Mechanical Properties.*

## 1. Introduction

Coal mining operations worldwide generate substantial quantities of solid waste, with coal gangue representing one of the most significant by-products. Conventional surface disposal of gangue presents serious environmental challenges, including land degradation, water contamination through heavy metal leaching, and potential spontaneous combustion hazards (Bian et al., 2012). In recent years, sustainable mining practices have emphasized the importance of solid waste recycling and reuse, particularly through backfill mining technologies that return processed waste materials to underground voids (Zhang et al., 2021).

Backfill mining technology has emerged as a comprehensive solution addressing both environmental concerns and geotechnical stability issues in underground mines. This approach not only mitigates surface waste accumulation but also provides effective ground support, reduces surface subsidence, and enhances resource recovery efficiency (Behera et al., 2021). The development of gangue-based backfill materials has consequently gained significant research attention, focusing on optimizing mechanical performance while maintaining economic viability.

Previous research has extensively investigated various aspects of gangue utilization in backfill applications. Zhang et al. (2021) examined the mechanical and deformation characteristics of cemented gangue backfill, establishing fundamental relationships between mix proportions and strength development. The role of binder composition has been thoroughly studied by Fall et al. (2020), who demonstrated how cementitious materials influence the rheological and mechanical properties of paste backfill. Chemical admixtures have been identified as crucial components for performance enhancement, with Li et al. (2022) investigating the effects of early-strength agents on hydration processes and strength development in gangue-based composites.

Microstructural investigations have provided valuable insights into the fundamental mechanisms governing backfill material behavior. Guo et al. (2022) utilized advanced analytical techniques to study pore structure evolution in gangue concrete, establishing correlations between microstructural changes and macroscopic performance. Long-term stability considerations have been addressed by Cao et al. (2021), who analyzed creep behavior and damage evolution in cemented gangue-fly ash backfill under sustained loading conditions.

Despite these extensive research efforts, a notable knowledge gap persists in the systematic optimization of gangue-based backfill materials tailored for TBM lining backfill in coal mines. The annular space behind TBM linings presents unique requirements, demanding careful balance between early-age strength development for immediate ground support and ultimate strength for long-term stability. The synergistic effects of water-cement ratios and multiple chemical admixtures in this specific application context require comprehensive investigation.

This study aims to develop an optimized gangue-based backfill material tailored for TBM lining applications through systematic laboratory experimentation. The specific objectives include:

1) evaluating the effects of water-cement ratio on compressive strength development.
2) investigating the influence of expansive agents, early-strength agents, and water-reducing agents on mechanical properties; and

3) analyzing the stress-strain behavior and failure characteristics under uniaxial compression at different curing ages.

## 2. Methods

### 2.1. Uniaxial compression test

#### 2.1.1. Specimen preparation

Waste gangue samples were collected from the working face of a deep roadway excavation to serve as bean gravel. Laboratory sieving was performed to prepare gangue bean gravel with a particle size of 5–10 mm for use as coarse aggregate. Specimens were cast into 100 mm × 100 mm × 100 mm cubic specimens. These were cured under standard conditions and extracted after curing periods of 1 d, 7 d, and 14 d, respectively.

#### 2.1.2. Raw materials and mix proportion design

Materials used in this experimental study include: P.O 42.5 cement, bean gravel (5–10 mm), expansive agent, early-strength agent, and water-reducing agent. Specimens were fabricated according to the designated mix proportions (see Table 1). Following casting, the specimens were subjected to curing, and uniaxial compression tests were performed in batches.


**Fig. 1:** Photographs of Experimental Materials.

**Table 1:** Mix Proportion Design

| Group | Water-Cement Ratio | Expansive Agent (%) | Early-Strength Agent (%) | Water-Reducing Agent (%) |
|---|---|---|---|---|
| 1-1 | 0.5 | 5 | 3 | 0.2 |
| 1-2 | 0.5 | 6 | 4 | 0.4 |
| 1-3 | 0.5 | 7 | 5 | 0.6 |
| 2-1 | 0.6 | 5 | 4 | 0.6 |
| 2-2 | 0.6 | 6 | 5 | 0.2 |
| 2-3 | 0.6 | 7 | 3 | 0.4 |

### 2.1.3. Test equipment and procedure

The uniaxial compression tests were performed using a WAW-1000 electro-hydraulic servo universal testing machine, as shown in Figure 2.

**Fig. 2:** The WAW-1000 Electro-Hydraulic Servo Universal Testing Machine Used for Uniaxial Compression Testing.

The tests were performed strictly in accordance with standard protocols and equipment operating procedures. A displacement-controlled loading method was adopted, with an axial displacement rate of 1 mm/min, until specimen failure. The system recorded load and displacement data throughout the loading process, which was subsequently processed to derive stress-strain curves. The peak strength of the specimen was defined as its uniaxial compressive strength.

Uniaxial compression tests were conducted sequentially based on the predefined mix proportions and curing ages. The specific testing procedure was as follows:

1) Specimens were labeled according to their group and curing age. Surfaces were prepared, and the testing machine platens were cleaned to minimize errors;
2) The loading apparatus was adjusted to ensure intimate contact with the specimen;
3) Upon completion of preparations, the testing machine was set to displacement control mode, applying a constant axial displacement rate of 1 mm/min until specimen failure, while recording the test data.

## 3. Results

### 3.1. Test data

The evaluation of uniaxial compressive properties was conducted in compliance with the Chinese national standard Standard for Test Methods of Concrete Physical and Mechanical Properties (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2019). Uniaxial compression tests yielded parameters including compressive strength (determined according to Section 7 of the standard), elastic modulus (determined according to Section 8), and deformation modulus of the backfill material specimens. For compressive testing, 100 mm cubes were used, with three specimens cast per mix proportion group. Uniaxial compression tests were performed on specimens after 1 d, 7 d, and 14 d of curing. The results are presented in Table 2.

**Table 2:** Uniaxial Compressive Strength (MPa) (Mean ± Standard Deviation, n=3)

| Group | 1 d | 7 d | 14 d |
|---|---|---|---|
| 1-1 | 23.5 ± 0.8 | 23.7 ± 0.9 | 25.0 ± 1.1 |
| 1-2 | 26.4 ± 1.2 | 31.7 ± 1.4 | 34.9 ± 1.6 |
| 1-3 | 35.3 ± 1.5 | 38.9 ± 1.7 | 41.1 ± 1.8 |
| 2-1 | 16.4 ± 0.7 | 16.6 ± 0.8 | 16.8 ± 0.9 |
| 2-2 | 32.8 ± 1.4 | 34.5 ± 1.5 | 40.1 ± 1.7 |
| 2-3 | 30.4 ± 1.3 | 34.4 ± 1.5 | 39.7 ± 1.7 |

**Table 3:** Elastic Modulus (GPa) for Different Mix Proportions and Curing Ages

| Group | 1 d | 7 d | 14 d |
|---|---|---|---|
| 1-1 | 1.8 | 2.0 | 2.1 |
| 1-2 | 2.1 | 2.5 | 2.9 |
| 1-3 | 2.7 | 3.0 | 3.2 |
| 2-1 | 1.2 | 1.3 | 1.3 |
| 2-2 | 2.5 | 2.7 | 3.1 |
| 2-3 | 2.3 | 2.6 | 3.0 |

Figure 3 illustrates the failure process of a gangue bean gravel backfill specimen during uniaxial compression. The primary failure mode is axial splitting. As compression proceeds, spalling initiates at the midsection and sides of the specimen, eventually leading to ultimate failure.

**(A) Intact Specimen Before Testing**

**(B) Intermediate Cracking Stage**

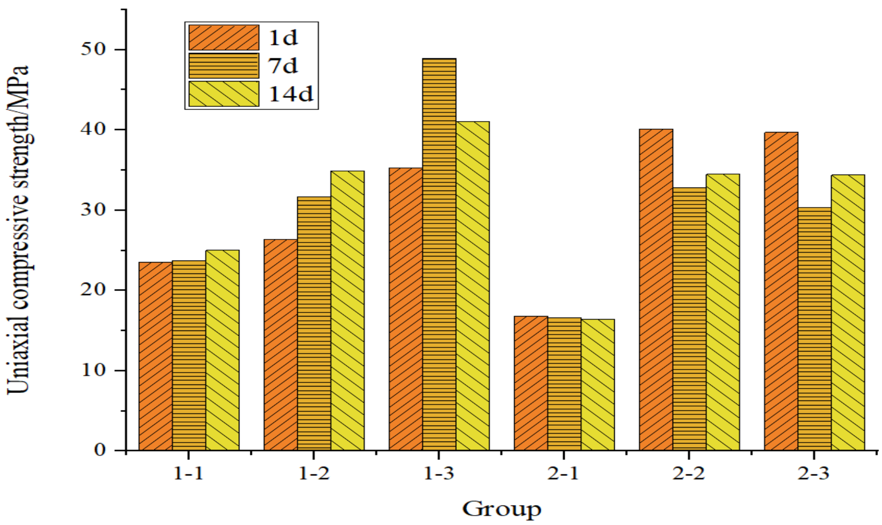
**(C) Final Failure with Axial Splitting**

**Fig. 3:** Typical Failure Sequence of A Bean Gravel Backfill Specimen Under Uniaxial Compression.

### 3.2. Stress-strain curves under different curing ages

Detailed laboratory results for different mix proportions and curing ages are shown in Figure 4. Specifically, Figure 4(a) presents the uniaxial compressive strengths for six mix proportions at different curing ages, while Figure 4(b) depicts the stress-strain curves from uniaxial loading tests for mix proportion Group 1-3 at various curing ages.

(A) Strength Development Trends for All Six Mix Proportions Across Curing Ages



(B) Representative Stress-Strain Curves for Optimal Mix Proportion (Group 1-3) at 1, 7, and 14 Days Curing

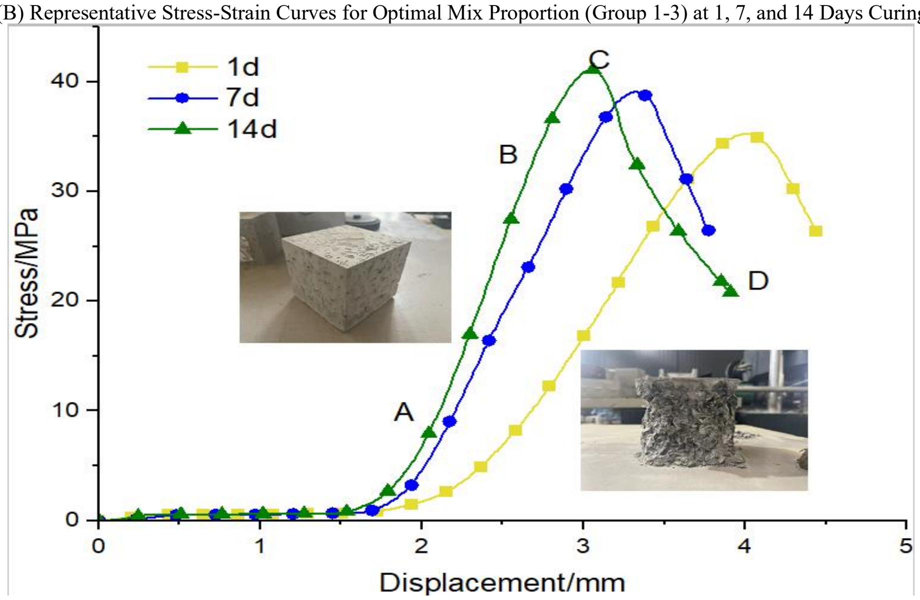



**Fig. 4:** Summary of Uniaxial Compression Test Results.

Figure 4 reveals that the stress-strain curves of the backfill material all exhibit strain-softening characteristics. The general trend of the stress-strain curves is consistent across different curing ages, and the peak stress increases with extended curing time. With increasing axial displacement, the specimens display a distinct initial compression stage characterized by a relatively flat curve, followed by an elastic stage where stress increases rapidly with axial displacement. This is succeeded by a crack development stage, and finally a failure stage where stress drops abruptly after the peak and subsequently stabilizes.

## 4. Discussion

### 4.1. Discussion of stress-strain behavior

The analysis of stress-strain curves reveals four distinct stages:

1) Compression Stage (OA): Since the particle size distribution and proportion of the bean gravel remain constant, the length of the compression stage remains largely unchanged with increasing curing age. However, the tangent modulus within the compression stage increases with prolonged curing.
2) Elastic Deformation Stage (AB): During this stage, under relatively low load, the coarse aggregates undergo elastic deformation, and the development of internal defects within the specimen is slow. The curve exhibits a nearly linear relationship.
3) Crack Development Stage (BC): As the axial load continuously increases, internal voids within the specimen are gradually compacted. Cracks initiate and propagate rapidly until the bearing capacity reaches its peak. The tangential modulus decreases with increasing strain, reaching zero at the peak point C.
4) Failure Stage (CD): Upon reaching the peak stress at point C, cracks on the specimen surface develop rapidly, manifesting as multiple vertical cracks. As cracking intensifies, the specimen begins to spall from the edges towards the center.

The differences in peak stress are relatively minor and are influenced by both mix proportion and curing age. The peak stress increases with longer curing times, and the peak load is attained more rapidly, aligning with the practical engineering requirements for high early strength and high ultimate strength.

### 4.2. Discussion of reinforcement mechanisms and microstructural implications

The proposed reinforcement mechanisms gangue interlocking, bonding through cementitious phases, and cementation are consistent with the observed stress-strain behavior and strength development trends. The interlocking of gangue particles contributes to the extended compaction stage and improved ductility, while the bonding and cementation processes enhance compressive strength, particularly with prolonged curing. These mechanisms explain why specimens with optimal admixture proportions (Group 1-3) achieved the highest strength and most rapid strength gain.

While this study focuses on macroscopic mechanical performance, the proposed mechanisms would be further validated through micro-structural analysis. Techniques such as scanning electron microscopy (SEM) could visualize particle interlocking and cementitious bond-ing, while X-ray diffraction (XRD) could identify hydration products and cementitious phases. Such microstructural investigations, as demonstrated in related studies on gangue concrete (Guo et al., 2022), would provide direct evidence of the interactive reinforcement model proposed here and offer deeper insight into the material's internal structure-property relationships.

### 4.3. Discussion of practical implications and research scope

This study provides a systematic laboratory evaluation of gangue-based backfill materials for TBM lining applications, with a focus on short-term compressive performance under varied mix designs. The mechanical properties within 14 days are the primary focus because, in TBM tunneling, the backfill material must achieve the required strength within this period to jointly bear the surrounding rock pressure together with the lining structure. Based on engineering experience, the surrounding rock deformation is relatively rapid within the first 14 days after tunnel excavation, and the surrounding rock tends to stabilize with minimal deformation after 14 days.

Concerning engineering application, this material has been successfully applied in the construction of the –820 m transportation tunnel at Zhangji Coal Mine. The roadway surrounding rock remains stable, and the support structure meets the requirements for controlling surrounding rock stability, demonstrating the practical feasibility of the proposed material.While this study provides important insights into early-age strength development, future research could extend the investigation to long-term durability indicators such as creep behavior, chemical stability, and resistance to underground water erosion. Additionally, field validation under varied geological conditions and microstructural characterization using techniques such as SEM or XRD would further strengthen the mechanistic understanding and practical applicability of gangue-based backfill materials.

## 5. Conclusion

This study fabricated specimens with varying water-cement ratios, admixture contents, and curing ages, and conducted uniaxial compression experiments, leading to the following conclusions:

1) Both the addition of admixtures and the extension of curing time contribute to improving the uniaxial compressive strength of the specimens. The maximum increase in uniaxial compressive strength of the specimens from 1 d to 14 d was 32.2%. For specimens with the same curing age but different admixture proportions, the maximum increase in uniaxial compressive strength reached 24.3 MPa.
2) The optimal performance was achieved with a water-cement ratio of 0.5 combined with admixture contents of 7% expansive agent, 5% early-strength agent, and 0.6% water-reducing agent. This mix proportion achieves the highest uniaxial compressive strength, the fastest strength growth rate with curing time, accelerated strength development beyond the initial compression stage, a higher peak compressive strength, and a shorter time to reach peak strength, thus meeting the requirements of practical TBM lining backfill engineering.

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