

Review

Strength Characteristics of Cemented Backfill: A Review of Current Coal-Focused Research and Innovations

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Abstract

Backfill mining is a key technique for achieving mine stratum control and synergistic disposal of solid waste. Cemented backfill, as the core bearing structure of the mined area, plays an essential role in ensuring engineering safety and promoting green mining practices. This review systematically explains the multiscale mechanisms of strength development in backfill and establishes a three-tier analytical framework based on “Materials–Environment–Structure”. At the material level, previous research has revealed the microscopic mechanisms involving hydration products and the interfacial transition zone (ITZ); at the environmental level, the coupling of multiphysical fields during strength evolution has become a focal point of study. The core challenge lies in the fact that large-volume backfill under field conditions, which forms layered structures, is anisotropic and exhibits size effects during sedimentation and processing stages, significantly controlling the macroscopic mechanical behavior. This is difficult to fully reveal through laboratory research focused on homogeneous materials. The authors provide a comprehensive review of experimental, simulation, and theoretical results, with a focus on revealing the controlling mechanisms of factors such as layered weak interfaces, inclined interfaces, and structural scale for backfill strength and failure modes. Moreover, the proposed “Materials–Environment–Structure” framework offers predictive potential for linking multiscale strength formation mechanisms with field-scale structural performance. The goal is to advance the understanding of strength from material constitutive models to structural responses, providing theoretical support for the development of strength prediction methods and structural designs suitable for engineering practice.

Keywords: cemented coal backfill; strength characteristics; structural level; anisotropy; size effect



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1. Introduction

Coal remains a critical foundational source of energy in the global energy system. In 2023, coal accounted for 26% of global primary energy consumption, with China consuming approximately 56% of the global total. This highlights its irreplaceable role in securing energy supply and stabilizing industrial production chains [1,2]. However, high-intensity mining activities have led to issues such as surface subsidence, groundwater disturbance, and the accumulation of large quantities of solid waste, which have become major factors

hindering the ecological safety and sustainable development of mining areas [3]. Driven by the “dual carbon” strategy, promoting green transformation in the coal industry, improving the utilization of solid waste resources, and constructing green mines have become the industry-wide consensus [4].

Among various green mining technologies, backfill mining has become an important means for achieving safe and efficient utilization of “three-down mining” (utilizing resource recovery and controlling surface subsidence) due to its advantages in controlling surface subsidence, increasing the rates of resource recovery, and synergistically disposing of solid waste. This review is grounded in the global literature on cemented backfill strength; however, given the large scale and high representativeness of coal-mine applications (particularly in China), related case evidence is presented with emphasis. As of 2025, at least 81 coal mines in China have adopted backfill mining techniques (Figure 1 and Table 1) [5]. Cemented backfill, as the main bearing structure in backfilled mined areas, can directly affect the stability of mined voids and the control of mining pressure [6]. Over the past decade, types of cemented material, aggregate gradation, water-to-binder ratios, and the use of solid waste replacement materials have been extensively investigated. These studies have clarified the roles of hydration products, pore structure, and the interfacial transition zone (ITZ) in the strength development mechanisms, and the mechanisms of strength at the material level have become relatively mature [7,8].

However, with the expansion of backfill engineering and the increasing complexity of in situ conditions, relying solely on material-level explanations can no longer meet the precision requirements for engineering strength predictions [9]. In practice, large-volume backfills often form heterogeneous structures due to factors such as slurry sedimentation, layered pouring, and differences in flowability, leading to significant spatial anisotropy and size effects on strength [10]. Meanwhile, environmental factors such as temperature, stress, and groundwater chemical conditions exhibit multiphysical field coupling characteristics, further complicating the evolution of strength [11]. Existing research tends to focus on single factors or local coupling relationships, lacking a cross-scale integrated understanding, leading to significant differences between laboratory experimental results and field behaviors [12,13].

Table 1. Overview of typical backfilling techniques in China’s coal sector (to 2024) [12].

No.	Mine	Province	Technique	Key Features
1	Xingdong	Hebei	Solid intelligence	First intelligent filling face
2	Xiaoji Han	Shaanxi	Resource synergy	Water-heat-coal synergy
3	Wanglou	Shandong	Cemented gangue	High-strength for subsidence control
4	Yuwu	Shanxi	Local materials	Eco-restoration & reuse
5	Dalong	Guizhou	Alkaline waste	Anti-acid gangue handling
6	Halagou	Inner Mongolia	Smart slurry system	Thick seam + automation
7	Santanghu	Xinjiang	Light foam mix	Low-water material of dry zones
8	Zhangji	Anhui	Neutral slurry	Flexible gangue mix
9	Shangwan	Inner Mongolia	Continuous filling	Model mine with full sensing
10	Zhangzhuang	Shanxi	Corner resource	High recovery from edge coal
11	Daizhuang	Shandong	Paste backfilling (three-under)	Village coal pressure relief and recovery enhancement
12	Taiping	Anhui	Strip pillar infill	Remnant pillar remediation and mine life extension
13	Wutongzhuang	Hebei	Backfilling under a confined aquifer	Prevention of Ordovician aquifer inrush and safety enhancement
14	Xiaoyaogou	Inner Mongolia	Hydraulic + eco-reclamation	Combination of mining with land restoration
15	Haoyuan	Anhui	Continuous mining-backfilling synergy	Realization of continuous mining-backfilling synergy

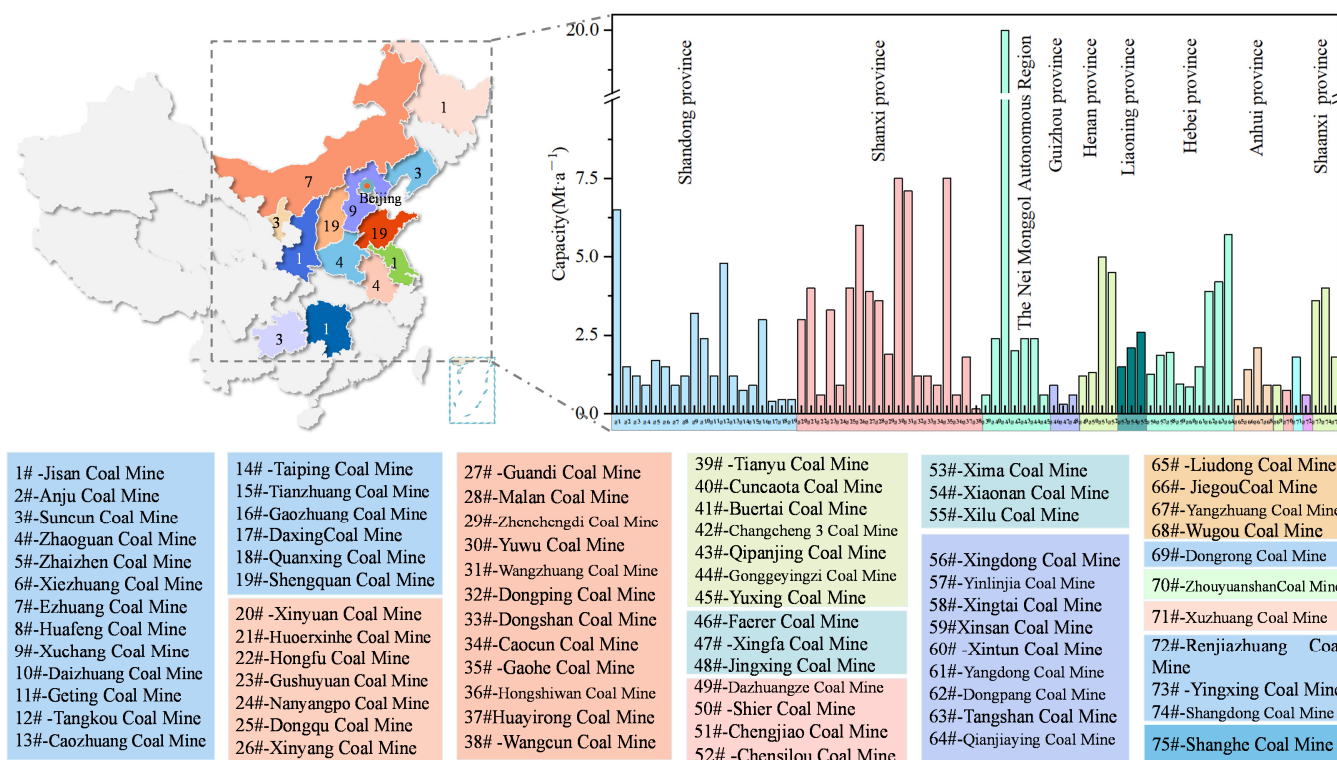


Figure 1. Distribution of select coal mines using backfill mining in China [12].

Based on the material, environmental, and structural three-tier framework, this review summarizes recent progress in research on aggregate gradation and morphology, cementitious material systems, ITZ characteristics, the influences of curing environments, and in situ layered structures. It analyzes their primary control mechanisms on the strength evolution of cemented backfill. Furthermore, the authors discuss the development of backfill materials and the size effect of CO₂ mineralized solid waste under structural control conditions, aiming to provide a systematic theoretical reference for the strength prediction and engineering design of cemented backfill.

2. Multiscale Mechanisms of Strength Development

The evolution of the strength of cemented backfill spans multiple levels, including material composition, curing environment, and sedimentation-layered structures, exhibiting characteristics typical of multiscale coupling. To establish a system for understanding strength that can simultaneously explain the differences between laboratory specimens and field applications, it is necessary to categorize the influencing factors hierarchically. This section starts with the sedimentation characteristics at the engineering site, revealing the mechanisms underlying the formation and mechanical significance of the “structural backfill”. Based on different dominant mechanisms in the preparation and curing processes, a classification system for factors influencing the strength at the material, environmental, and structural levels is established.

2.1. Formation and Mechanical Properties of Structural Backfill Materials

Given that the sedimentation process at the field site leads to the development of significant structural characteristics in cemented backfill, which cannot be fully reflected in laboratory specimens, this section first elaborates on the formation mechanisms and mechanical characteristics of “structural backfill”. Based on this, a hierarchical classification system for strength-influencing factors is constructed from the perspectives of materials,

environment, and structure, providing the theoretical foundation for the systematic review in subsequent sections.

2.1.1. Concept and Material Basis of Structural Backfill

On a microscopic level, cemented backfill is a heterogeneous multiphase composite material composed of aggregates, hydration products, unhydrated particles, and voids [14]. Its strength is primarily based on a three-dimensional (3D) network structure formed by hydration products, such as C-S-H gels [15], and is also constrained by the weak ITZ formed due to bleeding between aggregates and slurry [16]. However, this mechanism of material-level strength primarily applies to laboratory-prepared homogeneous specimens.

Although previous studies have deeply explored the hydration mechanisms, microstructure, and strength characteristics of backfill materials from the perspective of material composition and curing environment, the mechanical properties of backfill formed under engineering conditions are no longer completely dominated by material-level strength. Instead, they exhibit characteristics of a “structural backfill” [17]. The strength of the backfill is not only determined by material composition but, more importantly, evolves during the slurry deposition, hydration, and consolidation processes into a heterogeneous material with layered interfaces and non-homogeneous structures. This feature cannot be overlooked [18].

To further reveal the dominant mechanisms of the mechanical behavior of cemented backfill across different scales, this study compares the structural characteristics, anisotropy, size effects, and mechanical control mechanisms of rock, rock mass, laboratory-prepared backfill, and field-scale backfill, using natural rock and rock mass systems as references (Table 2) [13,19,20]. This comparison across material systems shows that as the scale increases from centimeters to meters and even hundreds of meters, there is a universal shift from “material-controlled behavior” to “structure-controlled behavior” [10].

Table 2. Comparison of strength characteristics between rock/rock mass and laboratory/field cemented backfill.

Comparison Dimension	Rock	Rock Mass	Laboratory-Scale Backfill	Field-Scale Backfill
Scale	Small-scale (cm level)	Large-scale (m–km)	Laboratory specimens (e.g., $\Phi 50 \times 100$ mm)	Stope-scale, large-volume
Structural features	Homogeneous, intact	Fractured, discontinuous, structure-controlled	Relatively homogeneous	Layered, inclined, and non-uniform interface
Anisotropy	Micro-crystal or textural	Macroscopic, joint-dominated	Weak anisotropy due to interface variation	Significant due to layering and interface inclination
Scale effect	Present but correctable	Strong, requires multiscale modeling	Moderate, manageable in tests	Strong, nonlinear field response
Mechanical control	Material constitutive behavior	Coupling of structure and material	Cementation and hydration structure	Dominated by layering, anisotropy, and scale

Rocks typically use centimeter-scale standard specimens (e.g., $\Phi 50 \times 100$ mm) as basic test units, exhibiting a relatively homogeneous and intact form at small scales—though containing microscopic heterogeneity, their spatial variability is weak, and mechanical behavior is dominated by material constitutive properties. Rock masses are meter to kilometer-scale geological bodies in natural geological environments, composed of rock units and macroscopic structural planes (joints, fractures, etc.), with mechanical responses resulting from the coupling effect of material and structure [17,21–23]. As shown in Table 2,

laboratory-prepared backfill specimens are small-scale homogeneous cemented bodies whose strength depends on the cementitious structure between hydration products and aggregate interfaces. Field-scale backfill is a large-volume engineering body in stope scales; influenced by in situ slurry deposition, bleeding, and consolidation processes, it forms heterogeneous interfaces and accumulation structures, with mechanical properties dominated by layered characteristics, anisotropy, and scale effects, converging with the “structure-controlled” logic of rock masses. In summary, rocks and laboratory backfill specimens are small-scale quasi-homogeneous material test units, while rock masses and field backfill are engineering-scale structure-dominated geological/engineering systems—the former provide the material basis for the latter, which shift from “material-controlled” to “structure-controlled behavior” with scale expansion and environmental effects. Therefore, at the engineering scale, cemented backfill is a typical “structural backfill”, and its macroscopic strength cannot be accurately characterized by material constitutive relations. Understanding must be enhanced through the mechanisms of structural formation and cross-scale evolution patterns.

2.1.2. Formation of Structural Backfill

Layered cemented backfill formed in large-scale mined-out areas is affected by geological conditions and mining processes. It can be considered as consisting of various matrix materials and layered interfaces. Taking the paste backfill mining process beneath buildings in a mine in Yulin City as an example, a single strip (8 m × 10 m × 120 m) is typically filled using two charging ports and corresponding exhaust ports for cooperation due to its large length (Figure 2a). The front end is filled first, and when the slurry reaches about 1–2 m below the roof, the deposition stops. At this point, under the effects of gravity, rheology, and bleeding, the slurry forms a slope at the front edge and a water accumulation zone at the rear edge (Figure 2b). Subsequently, the rear charging port is used to fill the remaining gap, forming a second sedimentation interface (Figure 2c). When the strength of both ends reaches a certain level, additional filling from either the front or rear end is performed to form sediment layers with different angles and thicknesses (Figure 2d,e). In this way, a layered structure with inclined layers can be formed within the single strip, as shown in Figure 2f–h [24].

On top of the layered single strip, the “8-mining, 24-retention” four-round strip filling substitution process further adds multiple temporal structures at the scale of the mined void. After the first round of strip curing, the second round of mining and filling was conducted, followed by the mining and filling of coal pillars between subsequent strips. The differences in the curing age, sedimentation height, and loading boundary conditions between different rounds of strips lead to additional contact interfaces and temporal stratification within the fill. This ultimately results in the formation of a layered cemented backfill with different shapes and angular layered surfaces.

Throughout the process of cemented backfill preparation, transportation, sedimentation, curing, and loading, the strength evolution is a comprehensive manifestation of the multiscale coupling of material, environmental, and structural factors. Material factors can determine the hydration reaction dynamics and the basis of the microstructure; environmental factors regulate the reaction rate, pore characteristics, and interfacial behavior; and structural factors ultimately control the stress transfer paths, anisotropic features, and failure modes. These three types of factors interact and collectively determine the complete mechanical strength evolution process of the backfill, from microscopic hydration products to macroscopic bearing behavior (Figure 3).

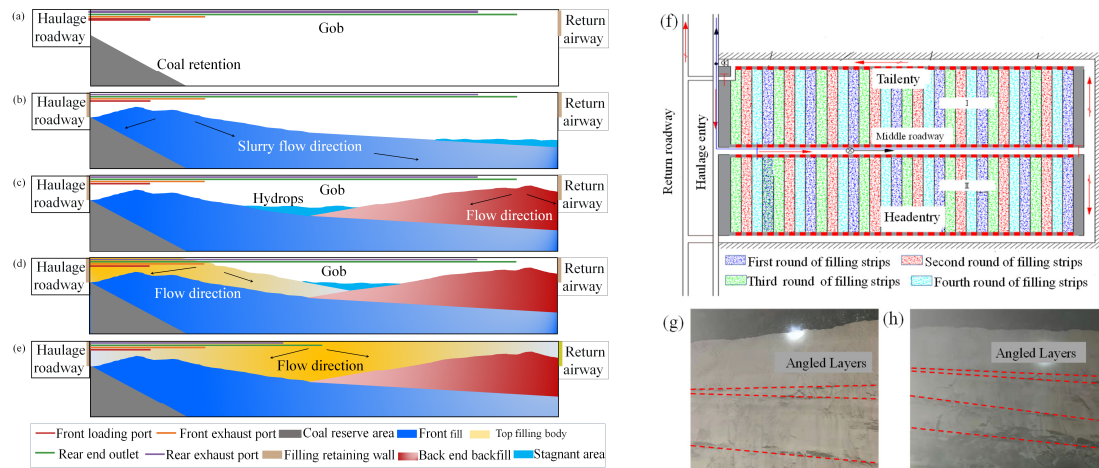


Figure 2. Formation of layered backfill with angles at different levels. (a) Schematic diagram of the layout of charging ports and exhaust ports for strip filling. (b) Slurry slope formed after the initial front-end filling. (c) Formation of the second slurry slope and water accumulation zone after rear-end filling. (d) Schematic of the backfill structure after front-end supplementary slurry filling. (e) Schematic of the backfill structure after rear-end supplementary slurry filling. (f) Schematic of the cyclic mining scheme for strip filling. (g,h) Photographs showing the layered interfaces formed after strip filling.

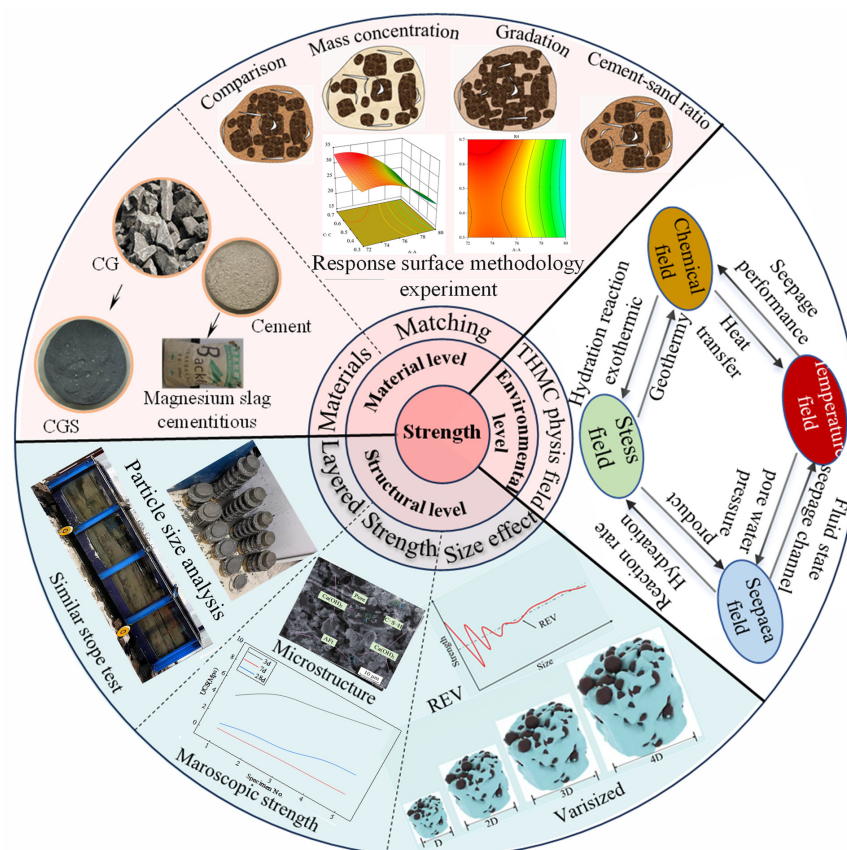


Figure 3. Formation of an angular layered backfill.

(1) Material level: this mainly includes the material composition, cementing system, and the characteristics of admixtures, which directly affect hydration reaction dynamics, gel structure composition, and ITZ performance. These factors serve as the initial conditions for the strength development, mainly corresponding to the microstructural hydration

and ITZ characteristics [16]. Material differences provide the theoretical upper limit of strength and are the microscopic source of the differences between laboratory specimens and engineering conditions in practice.

(2) Environmental level: the interactions of multiple physical fields, such as temperature, stress, seepage, and chemical environments, regulate the rate of hydration, pore closure, and interfacial evolution. These factors primarily correspond to the development mechanisms of strength under the influences of individual or coupled physical fields [11]. Environmental changes cause the same material system to exhibit different curing processes and strength evolution trajectories, making it a process-related influencing factor for strength.

(3) Structural level: affected by deposition methods, bleeding behavior, the topping process, and multi-stage mining and backfilling, in situ backfills form structural characteristics such as inclined stratification, accumulation transition zones, and size effects. These directly control the stress transfer paths, anisotropy, and macroscopic failure modes, which are the primary reasons for the deviation of engineering strength from laboratory results (Figure 4) [25].

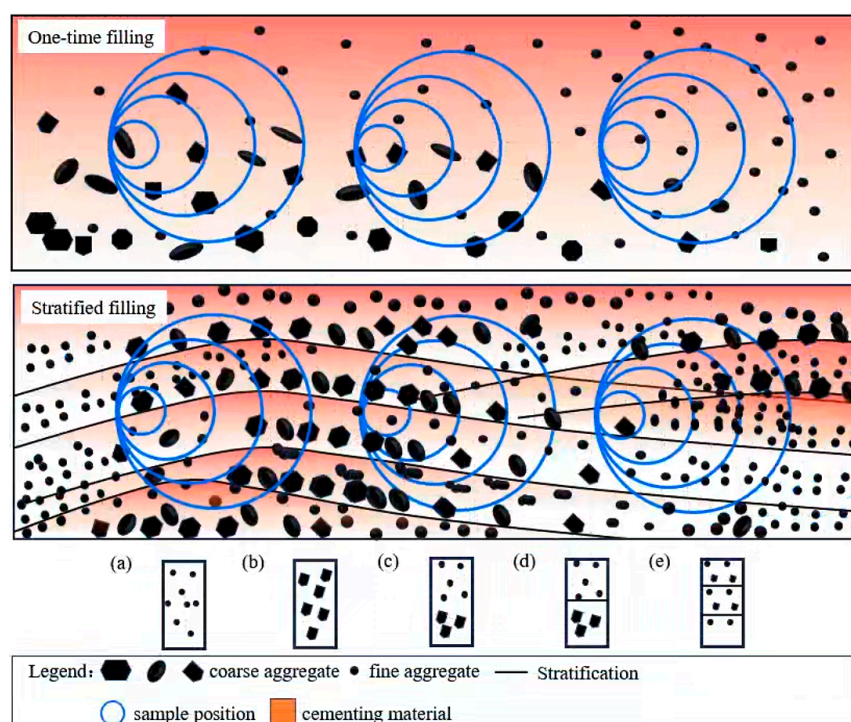


Figure 4. Schematic diagram of the size effect in backfill materials. (a) Fine particle concentration zone; (b) Coarse particle concentration zone; (c) Zone with fine particles both in upper and lower parts; (d) Zone with fine particles in upper part and coarse particles in lower part, with a single bedding plane; (e) Zone with multiple bedding planes.

In summary, the strength development and evolution of cemented backfill occur through multidimensional interactions of material composition, structural characteristics, and environmental conditions. The three factors separately control the mechanical behavior at different scales, together forming the complete strength evolution path from material reactions to structural bearing. Although existing research has focused on the individual effects of these factors or their partial coupling relationships, systematic multiscale collaborative studies remain relatively weak and warrant further development to support the accurate prediction of strength and optimization of engineering design. The subsequent sections comprise a systematic review of the influences of these factors at different levels.

2.2. Review Methodology

2.2.1. Database and Search

To improve the transparency of the review process, literature retrieval and screening were conducted around the topic of strength characteristics of cemented backfill. The literature was mainly collected from Web of Science, Scopus, ScienceDirect, and CNKI. The search primarily covered studies published from 2010 to 2025, with the finally cited studies mainly concentrated in the most recent five years. A small number of earlier classic studies closely related to the basic theory of cemented backfill, field-scale effects, and engineering applications were also retained.

The search terms mainly included “cemented backfill,” “cemented paste backfill,” “cemented coal backfill,” “strength characteristics,” “uniaxial compressive strength,” “hydration products,” “interfacial transition zone,” “aggregate gradation,” “alkali-activated binder,” “curing temperature,” “stress field,” “seepage,” “chemical attack,” “layered interface,” “anisotropy,” and “size effect.” Relevant Chinese terms with equivalent meanings were also used when searching CNKI.

2.2.2. Assessing Eligibility

The included studies mainly met the following criteria: the research object was related to the strength characteristics of cemented backfill, cemented paste backfill, or cemented coal backfill materials; basic information such as material composition, mix parameters, curing conditions, specimen size, loading method, or field boundary conditions was provided; the study discussed the effects of material composition, curing environment, or structural characteristics on strength formation, strength evolution, or failure modes; and the study could provide experimental, theoretical, numerical, or engineering-case support for the “Materials–Environment–Structure” analytical framework of this review.

For studies involving key numerical conclusions, priority was given to those with clearly described material systems, specimen geometries, loading conditions, and boundary conditions, in order to avoid overgeneralized comparisons beyond their applicable conditions.

2.2.3. Excluded Papers

First, papers were preliminarily screened based on titles, abstracts, and keywords, and studies weakly related to cemented backfill strength were excluded. Then, the full texts were reviewed to further exclude studies that only focused on non-cemented backfill or ordinary concrete without clear relevance to backfill engineering, studies lacking strength indicators or basic experimental conditions, duplicated or highly overlapping studies, and studies that provided insufficient support for the topic of this review.

In the final screening stage, representative studies reflecting different levels of influencing factors were retained, including studies on aggregate gradation, cementitious material systems, and interfacial transition zones at the material level; studies on temperature, stress, seepage, and chemical effects at the environmental level; and studies on layered interfaces, anisotropy, and size effects at the structural level. For studies with similar conclusions, priority was given to those with complete data, clear methods, explicit engineering backgrounds, or strong representativeness.

2.2.4. Data Extraction and Synthesis

To enhance comparability across studies and strengthen critical synthesis, this review treats “strength” as the central thread for consistent organization and cross-study comparison. For each key conclusion, we consistently extract and report the material system, mix/state parameters (e.g., solids content or w/b and equivalent indicators, binder–

aggregate ratio, activator/admixture scheme), curing/service environments (temperature, stress/drainage, seepage and chemical media), and specimen scale and boundary conditions (specimen geometry, loading scheme, and whether the specimen represents layered structural backfill or in situ coring). On this basis, strength-related findings are synthesized horizontally under the “Materials–Environment–Structure” framework.

2.3. Research Framework

Clarifying material properties and systematically reviewing the factors influencing strength are prerequisites for revealing the mechanisms underlying the strength development of cemented backfill. This research takes the complete engineering process of backfill from preparation to bearing as the main line, combining the multiscale characteristics of materials science and backfill engineering, and constructs a “Materials–Environment–Structure” three-tier classification system for strength-influencing factors. The overall research framework of this study is illustrated in Figure 5.

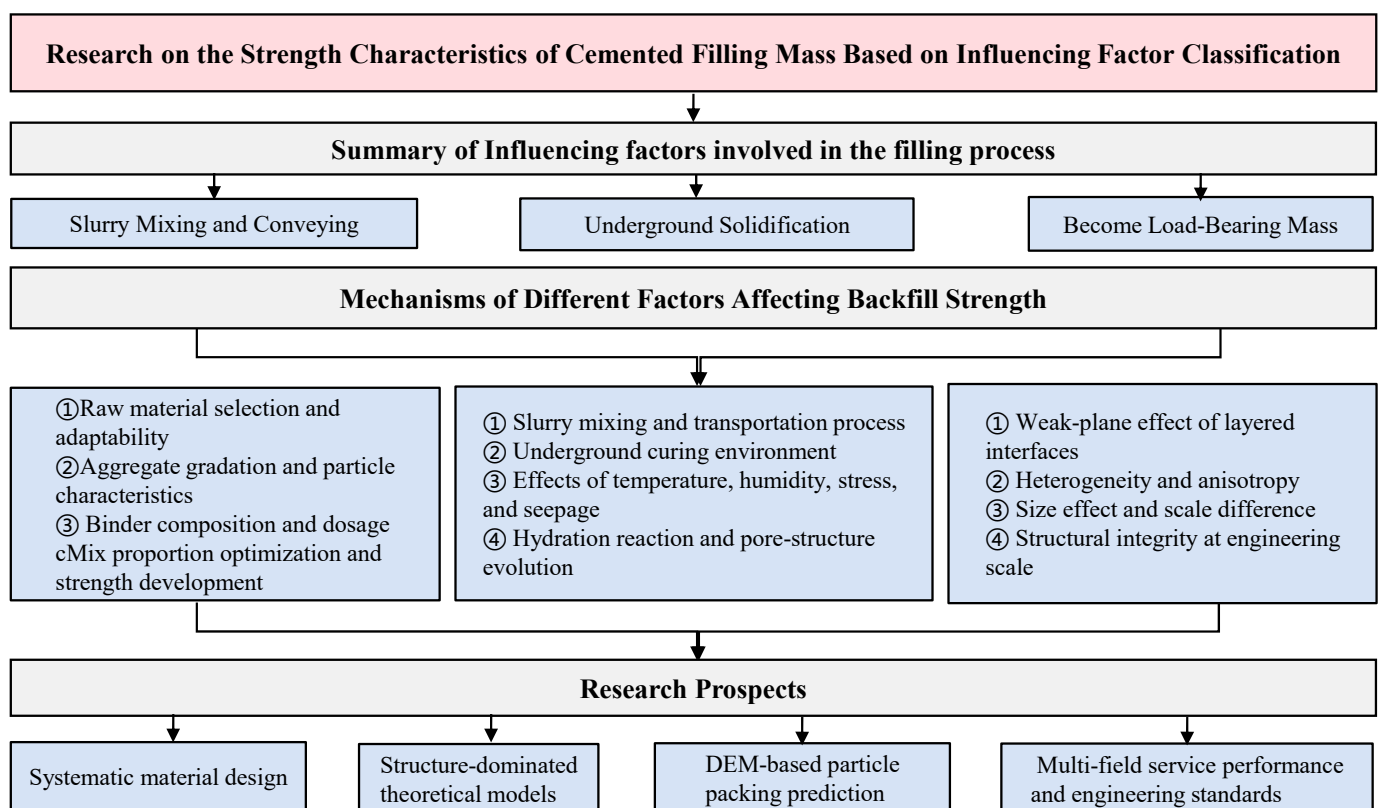


Figure 5. Schematic representation of the concepts underpinning the review.

First, starting with the composition of raw materials and microstructure, the influences of various factors at the material level on the development of strength in cemented backfill were analyzed. Next, the temperature, stress, seepage, and chemical conditions during the curing process were analyzed to explore the role of environmental factors in regulating hydration evolution and the strength evolution process. Finally, based on the anisotropy and size effects of backfill formed through field particle deposition and layered filling processes, the review reveals the control characteristics of the structural level on the strength distribution and failure modes at full scale.

On this basis, this review is organized according to the aforementioned logical sequence, systematically reviewing and analyzing the mechanisms of material, environmental,

and structural factors at different stages of the backfill engineering process, forming the organizational framework of the entire review.

3. Material-Level Influencing Factors

The material level forms the microscopic basis for the strength evolution of cemented backfill. Its properties determine the rate and extent of the hydration reaction, aggregate structure, and the initial state of the ITZ, and provide the foundational conditions for environmental effects and structural evolution. Based on this, the authors review the main mechanisms governing the material level of strength development from three aspects: aggregate gradation, cementing material system, and interface characteristics.

3.1. Optimization of Aggregate Gradation

Aggregates account for at least 60% of the total mass of backfill. The particle size distribution and morphological parameters of aggregates were optimized to establish a spatial packing structure that enhances the density and enlarges the contact area between aggregate particles. This improves the mechanical interlocking between aggregates, enhancing the packing density of particles, and is an important way of optimizing the mechanical performance of backfill and reducing filling costs [26].

Regarding the aggregate particle size distribution, it is widely believed that each type of aggregate has an optimal gradation. Excessive amounts of either coarse or fine aggregates will reduce the strength of the backfill and lead to different mechanical behaviors (Table 3). Within a certain range, appropriately increasing the content of fine aggregates generally helps improve the early-age strength of the backfill. However, beyond a reasonable range, an excess of any component will lead to a reduction in strength. Optimizing the content and gradation of coarse aggregates to form a good skeleton is more critical for ensuring later-age strength [27,28].

Due to significant differences in the sources and morphology of mining backfill aggregates, research conclusions on the effect of the particle size on the mechanical strength of backfill also vary widely. As shown in Table 1, no unified quantitative characterization method has been established, and it is difficult to determine the optimal aggregate particle size distribution design directly in practical engineering applications. The Chinese National Standard, “Technical Specification for Full Tailings Paste Backfill” (GB/T 39489—2020) [7], stipulates that the range of particle sizes for fine aggregates should be between 0.075 and 4.75 mm, and for coarse aggregates, it should be between 4.75 and 20 mm. Additionally, the content of particles smaller than 20 μm in full tailings should be greater than 15%. The Talbot gradation formula is commonly employed for evaluating the aggregate particle size distribution. The Japan Institute of Construction Industry has set the optimal range for the curve gradation index (n value) to be between 0.35 and 0.50. However, the Talbot gradation has limitations for irregular solid waste aggregates such as coal gangue, construction waste, ceramic waste, and waste rock. It mainly reflects particle size distribution, but cannot fully capture angularity, surface roughness, internal defects, and water absorption, which affect packing density, ITZ characteristics, and strength. Therefore, as indicated by Table 3, Talbot gradation should be calibrated according to aggregate morphology and mechanical response. Furthermore, the selection of aggregates for cemented backfill is gradually transitioning from windblown sand, loess, coal gangue, and tailings to building solid waste, gasification slag, and mixed tailings waste, aiming to achieve the goal of “treating waste with waste” [29].

Table 3. Summary of the optimal particle size ranges corresponding to different aggregates.

No.	Types of Aggregates	Optimal Gradation Index n or Particle Size Range	28-Day Uniaxial Compressive Strength/MPa	Reference
1	Ceramics	$n = 0.2$	3.42	[27]
2	Construction waste	$n = 0.4$	1.703	[30]
3	Coal gangue	$n = 0.6$	>28.0	[31]
4	Coal gangue	0.4–0.6	>7.0	[28]
5	Coal gangue	0–5 mm	>2.5	[32]
6	Coal gangue	5–10 mm accounts for 50% 10–20 mm accounts for 50%	8.9	[33]
7	Waste rock	Coarse aggregate accounts for 60%	>5.5	[34]

However, material-level prediction models based on gradation or particle packing remain limited because they simplify aggregate morphology, particle crushing, water absorption, and ITZ variability, making their parameters strongly dependent on aggregate type and mix conditions. Future research should focus on the synergistic mechanisms between the particle size and morphology of aggregates, developing multiscale and quantitative characterization and design methods. Advanced techniques, such as 3D printing and discrete element modeling, should be systematically introduced to more precisely quantify the parameters of aggregate morphology and reveal their regulatory effects on packing structures and interfacial strength, as well as on the surface reinforcement of aggregates [35,36]. Additionally, a strength-prediction model based on particle packing theory should be established to achieve precise control of backfill strength through optimizing gradation design. Ultimately, an intelligent design system integrating the physical properties of aggregates and their mechanical responses should be developed, promoting the transition of cemented backfill from empirical mix ratios to precise design.

3.2. Cementing Material System and Activation Mechanism

Cementing materials generate hydration products, fill the gaps between aggregates, and enhance their mechanical strength, making them key to formation. As material systems evolve from traditional cement to multi-type solid waste, their activation methods have expanded into complex synergistic mechanisms. This also represents a new research focus for high-performance and low-carbon backfill materials.

(1) Mechanical grinding

Mechanical grinding is the most commonly used method to enhance the cementitious activity of solid waste. The principle behind it is to increase the number of potential active reaction sites by refining particles, creating lattice structure defects, and increasing the specific surface area, or even converting the material into an amorphous state [37]. The main types of hydration products in the solid waste system do not change due to grinding; instead, the grinding process mainly reduces the hydration induction period and increases the rate of reaction. In other words, mechanical grinding improves the reaction kinetics rather than the reaction path, and the primary hydration products of the solid waste system remain unchanged by grinding [38].

The enhancement of activity through mechanical grinding follows the general rule of “moderate enhancement, but excessive grinding inhibits activity”: moderate grinding can expose active phases and improve early-age strength, while excessive grinding may lead to particle agglomeration, a decrease in the “effective utilization rate” of the specific surface area, and an increased water demand, thereby weakening the activation effect as shown in Table 4. Additionally, the grinding cost increases. Scholars typically use grinding kinetics

indices and cementing material activity indices as quantitative analysis methods [39]. Therefore, the mechanical activation effect depends on the defect density, particle size distribution, and their matching relationship with subsequent hydration kinetics.

Table 4. Summary of optimal grinding time and corresponding 28-day strength for different cementitious materials.

No.	Types of Cementitious Materials	Optimal Grinding Time (Min)	Unground 28-Day Strength/MPa	Grinding 28-Day Strength/MPa	Reference
1	Coal gasification slag (CGS)	60 (adding 10%)	46	53	[40]
2	FA	40	11	15	[41]
3	Magnesium slag	60	>3	>5	[42]
4	Magnesium slag	80	10.183	10.975	[43]
5	Gold mine tailings	80	No strength	2.59	[44]
6	CGS	20	11	16	[45]

Overall, previous studies have demonstrated the efficiency of mechanical grinding in activating solid waste. However, the diverse sources of solid waste lead to significant differences in grinding responses, and a universal grinding-activation model has yet to be established. Moreover, high grinding energy consumption and the lack of a systematic design method for the optimal matching of grinding energy and activation efficiency remain challenges.

(2) Chemical activation

Chemical activators accelerate the dissolution of active silica-alumina phases in solid waste and promote the formation of gel products by regulating the system's pH, ionic strength, and dissolution-precipitation equilibrium. This is a core pathway for achieving early-age strength in solid waste cementing materials [46]. Alkaline activation systems (such as NaOH and water glass) can form N-A-S-H and C-A-S-H gels, making them suitable for potential reactive materials such as slag and fly ash. Sulfate activation promotes the formation of AFt (ettringite) by adjusting the $\text{Ca}^{2+}/\text{SO}_4^{2-}$ balance, thereby improving the pore structure [47]. Composite activation systems can simultaneously trigger multiple reaction pathways, exhibiting higher compatibility in multi-type solid waste systems [48]. In CPB, NaOH-soda residue-activated GGBS combined with iron tailings achieved a fluidity of 267.5 mm and 28-d UCS of 2.4 MPa, with C-S-H/C-A-S-H gels and Friedel's salt, showing that alkali-activated binders can deliver both workability and strength [49,50]. For one-part AAS CTB, mixing-water chemistry reshapes gel chemistry and pores (Na^+ -driven C-A-S-H decalcification and 0.01–0.1 μm micropores vs. Ca^{2+} -induced densification) [6]; sulfate-temperature-time coupling elevates viscosity during transport through enhanced ettringite/hydration [8], alkaline pore solutions may disintegrate gangue unless protected by a strengthening "shell layer" [36], and long-term stability can be sensitive to coupled service environments (e.g., $\text{Na}_2\text{SO}_4 + \text{NaOH}$ activation and seepage-stress coupling) [10].

Although the overall patterns are relatively clear, significant differences in the composition of solid waste, glass phase content, and specific surface area make the activation threshold, reaction contribution, and the types and quantities of gel products highly dependent on the material. Additionally, the synergistic mechanisms between the chemical activation, mechanical activation, and thermal activation have yet to be established, and there is no unified method for quantitatively controlling key reaction pathways.

(3) Additives

The system of additives for mining cemented backfill differs from that of ordinary concrete, as its primary focus is on improving fluidity, controlling setting time, enhancing

early-age strength, strengthening corrosion resistance, and maintaining control over the cost. Previous studies have shown that the adsorption and dispersion behaviors of water-reducing agents are strongly affected by the surface chemistry and specific surface area of the solid waste, with their effectiveness exhibiting significant material dependency in high-dose solid waste systems [49]. Early-strength agents and accelerators can reduce the setting time and improve early structural stability, but in composite systems such as slag-fly ash, they often exhibit both promoting and inhibiting behaviors, reflecting the competitive nature of multiphase reaction pathways [50]. Retarders affect the formation rate of C–S–H and the pore structure by adjusting the chemical environment of the solution, playing a significant role in the long-term evolution of strength [51]. Air-entraining agents can optimize the pore morphology and enhance the stability of ITZ, but their effectiveness is highly affected by the morphology and surface activity of the solid waste particles [52].

Overall, while the mechanisms underlying the action of additives in cement systems are relatively well understood, those pertaining to the action of additives in solid waste systems characterized by complex compositions and diverse reaction pathways have yet to reach a systematic consensus. In particular, the compatibility mechanisms of different functional additives with multi-type solid waste, as well as their effects on interfacial behavior, remain key areas where knowledge remains insufficient.

(4) Synergistic activation of multi-type solid waste

Synergistic activation of various solid waste materials (such as fly ash, slag, steel slag, and red mud) in cementing systems has become an important approach to enhance early-age strength, improve the pore structure, and achieve decarbonization. The chemical composition, reactivity, and mineral structure of different solid wastes vary significantly; however, they often exhibit complementary effects in composite systems [53]. The synergistic activation effect primarily arises from three aspects: first, the chemical components of different solid wastes complement each other during the dissolution process, rendering the type and proportion of gel products more reasonable; second, the complementary time scales caused by differences in reaction rates allow for gradual gel formation and continuous filling of pores; third, the differences in particle sizes and morphologies lead to higher packing density and more continuous slurry encapsulation, which can help improve the structural uniformity of the ITZ region [54]. For example, steel slag with its high CaO content can increase the alkalinity of the system and provide soluble Ca^{2+} , promoting the formation of C–S–H and C–A–S–H gels. The amorphous silica-alumina components in fly ash and red mud are further activated in an alkaline environment to generate aluminosilicate gels, improving the structural density and the stability of later-age strength (Table 5).

Table 5. Overview of the development of novel, fully solid-waste-based backfill materials and additive research.

No.	Raw Materials	Variables	Content	Main Conclusions	Reference
1	Modified magnesium slag, fly ash, and desulfurized	Gypsum dosage (0, 2.5, 5.0, 7.5, 10 wt%), curing time (3, 7, 14, 28, 56 d)	Uniaxial compressive (UCS), leaching test, x-ray diffraction (XRD), Fourier Transform Infrared Spectroscopy (FTIR), SEM	Desulfurized gypsum significantly activates Mg slag-fly ash binder, enhancing strength and improving environmental performance for backfilling.	[46]

Table 5. Cont.

No.	Raw Materials	Variables	Content	Main Conclusions	Reference
2	Coal gasification slag, modified magnesium slag, aeolian sand	Activator type (CaCl ₂ , NaOH, Na ₂ SO ₄ , Na ₂ SiO ₃), activator dosage (0, 1, 2, 3, 4 wt%), grinding time (45, 60, 75, 90 min)	UCS, setting time, XRD, SEM, leaching test	Physico-chemical activation enhances low-activity CGS; material meets strength and environmental standards for mine backfilling applications.	[47]
3	Granulated blast furnace slag, calcium carbide residue, dihydrate phosphogypsum	Dosages of granulated blast furnace slag (0, 20, 40 wt%), calcium carbide residue (0, 2, 4, 6), and polycarboxylate superplasticizer (0.5 wt%)	UCS, XRD, SEMEDS, TG, PH, ICP-OES	Optimized dihydrate phosphogypsum-based backfill shows high fluidity, low bleeding, and improved strength and durability.	[48]
4	Granulated blast furnace slag, steel slag, and desulfurization gypsum	Copper slag proportion (0.3, 0.4, 0.5), steel slag dosage (30, 35, 40 wt%), binder-aggregate ratio (0.14, 0.17, 0.20)	UCS, XRD, FTIR, SEM	Solid waste-based cemented paste backfill (CPB) strength was optimized via response surface methodology and machine learning; the hydration mechanism was clarified; the result supports solid waste recycling in backfill mining.	[49]
5	Soda residue (SR), ground-granulated blast-furnace slag (GGBS), iron tailings, NaOH	Mass content (73, 74, 75, 76, 77%); GGBS content (10, 12, 14, 16, 18, 20%); activator-to-binder ratio (0.3, 0.4, 0.5, 0.6, 0.7); NaOH/SR proportion (30:70, 25:75, 20:80, 15:85, 10:90). Optimal design: 75% mass content, 14% GGBS, activator-to-binder ratio 0.4, NaOH:SR = 20:80.	UCS, XRD, SEM-EDS, FTIR, TG-DTG	Alkali-activated solid waste binder system yields the optimal strength; hydration products enhance the backfill performance through synergistic effects.	[50]
6	Electrolytic manganese residue (EMR), carbide slag (CS), and phosphorus slag (PS)	Mass fraction (70%): EMR (25, 30, 35, 40, 45, 50%), PS (65, 60, 55, 50, 45, 40%)	UCS, XRD, FTIR, SEM, NMR	Ternary EMR-CS-PS backfill achieves strength development and heavy metal stabilization through synergistic hydration and microstructural optimization.	[51]
7	Tailings, P.C 32.5, <i>Acidithiobacillus ferrooxidans</i> , <i>Acidibacillus ferrooxidans</i> , <i>Escherichia coli</i> , and <i>Leptospirillum ferriphilum</i>	Cement/fly ash-to-tailings ratio 1:4, 1:5, 1:6, deionized water, bacteria solution (0, 25, 50, 75, 100 wt%), and the proportion of fly ash to fly ash/cement (0, 10, 20, 30, 40 wt%).	TG, SEM, FTIR	Bacteria–fly ash binder enhances the strength of cemented tailings backfill (CTB), reduces permeability, and modifies microstructure via biomineralization and gel formation.	[52]

Table 5. Cont.

No.	Raw Materials	Variables	Content	Main Conclusions	Reference
8	<i>Sporosarcina pasteurii</i> , Yellow River Sand, calcium chloride, and urea	CaCl ₂ and CO(NH ₂) ₂ concentration (0.5, 1.0, 1.5, 2.0, 2.5, 3.0 mol/L); CaCl ₂ :CO(NH ₂) ₂ (1:1); bacterial solution/cementation solution volume ratio (2:1, 1:1, 1:2, 1:3, 1:4, 1:5); solids content (70, 72, 74, 76, 78%); enzyme activity (4.67–73.10 mmol/min).	UCS, XRD, FESEM, TG	Microbial mixed backfill enhances backfill strength via microbial-induced carbonate precipitation; strength depends on the CaCO ₃ morphology, cementation solution, and solid content.	[53]
9	Iron mineral tailings, cement, water	Cement-to-tailings ratio: (1:6); solid concentration: (70 wt%); water (243 g); binder (81 g)	UCS, XRD, TG/DTG	Microwave curing accelerates the early-age strength development and hydration of CTB, offering a method for the backfill performance.	[54]
10	Lithium feldspar tailings, ordinary Portland cement 42.5 R, polypropylene fibers, polyacrylonitrile fibers	Fiber types: PPF, PANF, GF; fiber length: 12 mm; cement-to-tailings ratio: 1:6 for fiber-reinforced samples; blank control: 1:4 and 1:6; mass concentration: 75%; fiber content: 0, 0.3, 0.6, 0.9 wt%	UCS, failure modes, SEM	Glass fiber optimally enhances the strength and ductility of cemented lithium feldspar tailings backfill; 0.6% content improves UCS, crack resistance, and energy dissipation.	[55]
11	Portland cement (P-I 42.5), silica fume (SF), sand, SiC, steel fibers, polycarboxylate superplasticizer (SP)	Steel fiber content (0, 0.5, 1.0, 1.5 vol%); water-to-binder ratio (0.4); binder-to-sand ratio (0.5); SP dosage (0.5%–1.5% of binder); defoamer (0.1); steel fiber diameter (0.2 mm), length (13 mm).	UCS, XRD, SEM-EDS	SiC and steel fibers increase thermal conductivity and enhance the mechanical strength of backfill; the fiber dosage optimizes the energy pile performance.	[56]
12	Waste polyethylene terephthalate and polyvinyl chloride, ordinary Portland cement (P.O 42.5), tailings	Particle sizes (100 µm, 500 µm, 3–4 mm); microplastic contents (0, 10, 20, 30 wt% relative to tailings); solid content: (70 wt%); curing age (7 d).	UCS, XRD, SEM-EDS	Waste polyethylene terephthalate microplastics enhance the strength of CTB at optimal dosage; offer a sustainable solution for plastic reuse and tailings management.	[57]

Table 5. Cont.

No.	Raw Materials	Variables	Content	Main Conclusions	Reference
13	CaCl ₂ , cement, fly ash	Cement:fly ash (coal gangue = 2:4:4); solid mass fraction (78%); maximum gangue particle size (8 mm); gangue gradation (<0.5 mm 21%, 0.5–1 mm 16%, 1–2 mm 17%, 2–4 mm 24%, 4–8 mm 22%); CaCl ₂ dosage (0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1, 2, 3, 4, 5%)	Setting time, rheological properties, UCS, XRD	CaCl ₂ (0.3%–0.5%) optimizes setting time and microstructure of gangue-cemented paste backfill, improving the performance of long-distance pipeline transport.	[58]
14	Modified magnesium slag, coal-fired slag, desulfurized gypsum, mineral powder, CaCl ₂ , Na ₂ SO ₄ , and Na ₂ SiO ₃	Fly ash:coal gangue = 18:20:62; slurry concentration = 76%; total inorganic salt dosage = 3% of the composite cementitious material; inorganic salt system = CaCl ₂ , Na ₂ SO ₄ , and Na ₂ SiO ₃ single/binary/ternary combinations designed by the triangular orthogonal method.	UCS, TG-DTG, SEM-EDS, ICP-MS, ICP-MS	Inorganic salts enhance the early-age strength and reduce the leaching risk of coal-based backfill; 28-day leachate meets Class III groundwater standards.	[59]
15	Tailings, Portland cement, superplasticizer	Tailings type; Portland cement dosage (3, 4.5, 6 wt%); polycarboxylate ether-based superplasticizer dosage (0, 0.125, 0.25, 1.00 wt%).	UCS, TG/DTG, MIP, SEM	Polycarboxylate ether-based superplasticizer enhances the strength of CPB; 3–7 day UCS is improved under stress and heat, influenced by dosage, tailings fineness, and curing conditions.	[60]

Although the synergistic activation system shows significant potential, the complexity of material composition also presents challenges in mix design. The differences in mineral structure, impurity content, and reactivity of various solid wastes make it difficult to generalize the key factors governing the activation reactions. Future research should establish predictive design methods based on mineralogical characteristics and develop quantitative relationships between chemical reactions, kinetic processes, and microstructural evolution to support the engineering applications of high-dose solid waste systems.

(5) CO₂ mineralization

The CO₂ mineralization route can be classified into direct, indirect, and integrated absorption-mineralization [61]. Among these, direct mineralization features a shorter process and lower cost, making it the current focus of much research. It can be further subdivided into dry and wet methods: the dry method involves gas-solid reactions and proceeds at a relatively slow rate. In contrast, the wet method, which introduces water to form a slurry, offers superior mass transfer and faster reaction kinetics, establishing it as the predominant approach (Table 6).

Research into the wet mineralization method is extensive; for instance, Liu Zhifei et al. [62] investigated the reaction kinetics of solid wastes such as steel slag and fly ash using

a direct wet method. Zhou Nan et al. [63] proposed a “whole-process carbonation” strategy, dividing mineralization into two stages: stirring and curing. The stirring stage utilizes mechanical forces to accelerate CO₂ dissolution and ion leaching, while the curing stage relies on hydration and CO₂ diffusion to continue carbon sequestration. The combination of both stages enables a greater total CO₂ uptake. Furthermore, to counteract the reduction in the rate of reaction caused by product layer encapsulation, techniques like wet grinding and carbonation were applied more continuously to expose fresh surfaces and drive the reaction forward [64].

The effectiveness of mineralization is primarily evaluated by CO₂ uptake and carbonation efficiency, both of which are closely tied to the composition of the solid waste itself [65,66]. The carbonation potential varies significantly among different solid wastes: steel slag typically ranges from 52–310 gCO₂/kg, red mud from 5–175 g/kg, fly ash from 11–210 g/kg, and desulfurization gypsum from 53–128 g/kg [67]. Liu Zhifei et al. conducted experiments at a pressure of 0.3 MPa at 25 °C and showed that steel slag achieved a CO₂ uptake of 136.1 gCO₂/kg, significantly higher than that of fly ash (81.86 gCO₂/kg) and bottom ash (16.2 gCO₂/kg) [62].

These disparities mainly arise from the different forms of calcium present [68–70]. Although steel slag has a high CaO content (42.47%), a substantial portion of the calcium is locked within less reactive calcium silicates, resulting in a carbonation efficiency of only 28.9%. Fly ash has a lower CaO content (25.06%), but its calcium exhibits higher reactivity, yielding a carbonation efficiency of 41.6%. Bottom ash has both low calcium content (14.11%) and a high proportion of inert components, resulting in a carbonation efficiency of merely 12.7%. Process conditions are also crucial. For example, in “whole-process carbonation,” the stirring stage contributes approximately 0.66%–3.10% to the CO₂ uptake, while the curing stage can reach 3.53%–5.09%. When combined, the total uptake reaches 5.12%–6.02%, indicating that optimizing pressure and temperature in separate stages can increase the overall amount of carbonation [62]. To improve the mineralization capacity of alkaline solid wastes, approaches include adjusting process parameters such as the liquid-to-solid ratio and temperature and employing mechanical activation and chemical additives. Moreover, the synergistic utilization of multiple solid wastes for mineralization can help increase the carbonation rate, enhance the compressive strength by 49.1%, and reduce water absorption by 20% [67].

Regarding the influence of mineralization on material strength, it can be generally recognized that carbonation is conducive to the strength development of backfill materials. For instance, materials such as magnesium slag can achieve an increase in 7-day strength of more than 25 times after carbonation curing, as the generated calcium carbonate fills the pores [65,71]. However, other studies indicate that mineralization may reduce the cementitious activity of materials such as steel slag and fly ash, causing a strength decrease of around 70%. This is primarily attributed to the consumption of active calcium, and the calcium carbonate formed on surfaces may also cause interfacial weakening [67]. The underlying mechanisms require further in-depth clarification.

Future development of CO₂ mineralization as a technique will focus on three key directions: first, enhancing the mechanism of mineralization through process, chemical, and mechanical means to overcome kinetic limitations; second, utilizing co-mineralization of multiple solid wastes to achieve compositional complementarity, thereby improving efficiency, reducing costs, and optimizing product performance; third, leveraging machine learning to optimize the assessment of life cycles, employing data-driven models to improve the efficiency and accuracy of evaluations [63,67,69,72].

Table 6. Preparation of carbon-negative filling materials.

No.	Raw Material	Mineralization Mode	Main Conclusion	Reference
1	Fly ash, carbide slag, FGD gypsum, gangue	Sealed stirring within the mixer	The cement-to-water ratio (RW-C) is the dominant factor influencing the CO ₂ sequestration capacity and compressive strength (negatively correlated with RW-C) of coal gangue mineralized backfill materials, and the CO ₂ sequestration process improves the compressive performance of the materials.	[73]
2	Fly ash, coal gangue, modified magnesium slag	CO ₂ curing: 20 (±1) °C, at a humidity of 60 (±2)%, and a CO ₂ concentration of 99%	Carbonation curing enhances the 7-day compressive strength of the magnesium-coal solid waste backfill material by 10.91 times, significantly densifies the microstructure, and achieves a maximum CO ₂ sequestration capacity of 14.3% and a carbonation efficiency of 92.2%.	[74]
3	Portland cement, water, Al/	Constant temperature and pressure reaction chamber system	Experimental results show that within 48 h, increasing the initial water-to-binder ratio, specimen porosity, and CO ₂ pressure can respectively increase the CO ₂ consumption rate by 15%, 10%, and 7%, providing key parameters for optimizing the CO ₂ sequestration capacity of this cement backfill material.	[75]
4	White Portland cement 42.5R, tailings	Introduce CO ₂ during stirring	Injecting 99% CO ₂ into the filling slurry at a rate of 1 L/min for 10 min in an open container can densify the pore structure of carbonated CPB, enhance its strength, and achieve 6.42% carbon sequestration. However, if the carbonation time is too long, a closed layer will form, hindering the diffusion of CO ₂ and reducing efficiency.	[70]
5	Coal gangue/modified magnesium/fly ash	Aerated stirred reaction	After CO ₂ absorption, the 28-day compressive strength of CO ₂ -MCSB is increased by 0.514–3.103 MPa, and the rate of carbon sequestration reaches 5.6–6.8%. Carbonation promotes hydration, forming needle-like Aft, C-S-H, and microcalcite to fill the pores, significantly enhancing strength.	[76]
6	Modified magnesium slag, fly ash, coal gangue	CO ₂ curing: at 20 (±1) °C, and a humidity of 60 (±2)%, and a CO ₂ concentration of 99%	Carbonation significantly enhances the compressive strength of backfill, with the depth increasing over time, then stabilizing. The later the initial carbonation age, the faster the increase in strength and depth. High-concentration CO ₂ curing causes the diffusion of CO ₂ , increasing the degree of carbonation, and decreasing the content of CaCO ₃ from the outside to the inside, improving long-term stability and airtightness.	[74]
7	Red mud/phosphogypsum/fly ash	CO ₂ curing: at 20 (±1) °C, a humidity of 60 (±2)%, and the CO ₂ concentration of 99%	Solidification with 20% CO ₂ for 28 h yields a strength of 31.6 MPa for RMPCM. The strength is enhanced by the filling of pores with CaCO ₃ and secondary C-S-H. Excessive curing time leads to weak acid erosion. Only Cr leaching exceeds 1 ppm, while other heavy metals significantly decrease within 15 min. A full life-cycle analysis demonstrates significant emission reduction.	[77]
8	Carbide slag, red mud, fly ash	CO ₂ mineralization reaction set-up (with aeration during stirring)	The strength of the FA-CS-RM composite filling material (F60C20R20) for CO ₂ mineralization is 14.9 MPa, an increase of 32.2%. The maximum solid storage is 14.4 kg·t ^{−1} , with an annual reduction of 1.23 Mt. About 0.18 Gt of CO ₂ can be sequestered in the Yellow River Basin.	[78]

3.3. ITZ

The ITZ, originally defined in concrete-related research, refers to the weak transitional layer between aggregates and the cementitious matrix. Its formation is primarily ascribed to the wall effect (non-uniform packing of fine particles around coarse aggregates) and the micro-bleeding effect (local accumulation of water in the interfacial region), resulting in higher porosity, lower degrees of hydration, and inferior mechanical properties (e.g., Young's modulus, nanoindentation hardness) compared with the matrix [79]. Studies have shown that the pore structure and elemental distribution of the ITZ exhibit spatiotemporal evolutionary features: the region adjacent to the aggregate contains more

pores, and the ITZ width increases with curing age due to shrinkage during setting [16]. In addition, some researchers introduced coupled thermal–hydraulic–mechanical–chemical (THMC) models to elucidate the effects of temperature and pore-water pressure on the ITZ performance [80].

To improve the mechanical performance of the ITZ, fiber reinforcement has become the mainstream strategy. Some researchers also explored biomass fibers such as corn straw, which improve ITZ toughness, crack resistance, and overall stability through mechanisms including mechanical interlocking, crack bridging, and microstructural densification [81,82].

Most existing studies are based on idealized laboratory conditions, with limited attention to the long-term performance and durability of the ITZ under real service environments. Moreover, the synergy between multi-field coupled models and experimental data remains insufficient. Future research should focus on multiscale simulation to link microstructural characteristics with macroscopic behavior and explore green, low-cost modification materials to promote engineering applications.

4. Environmental-Level Factors Influencing Curing

Once the raw materials and mix proportions are determined, the curing environment becomes the dominant external factor governing the strength evolution of cemented backfill. Temperature, stress, chemical conditions, and seepage—acting as coupled multiphysical fields—can jointly affect hydration kinetics, pore structure development, and interfacial behavior. Consequently, the backfill exhibits pronounced environmental sensitivity throughout its evolution, from initial setting to long-term strength development.

4.1. Temperature Field

Temperature can profoundly influence the entire strength development process of cemented backfill—from early structural formation to long-term mechanical stability—by regulating hydration kinetics, dissolution–precipitation equilibria, and microstructural evolution. Previous research primarily focuses on initial temperature, low-temperature conditions, isothermal curing, and thermal damage under extreme temperatures.

(1) Effect of initial temperature (0–50 °C)

The initial temperature primarily affects the early hydration kinetics during mixing and casting. Studies have shown that strength exhibits a nonlinear relationship with initial temperature: within the range of 20–35 °C, an increase in temperature significantly accelerates the rate of deposition of C–S–H and Aft, thereby enhancing early densification; however, excessively high initial temperatures lead to the rapid formation of a dense encapsulation layer on aggregate surfaces, impeding ion diffusion and causing insufficient internal hydration, ultimately suppressing the development of later-age strength [83].

This dual mechanism—simultaneous “hydration acceleration” and “transport limitation” [84]—is currently underestimated in most temperature-related models. Existing studies predominantly focus on macroscopic strength behavior, lacking direct evidence relating to the formation, structural attributes, and long-term effects of the encapsulation layer. Future work should adopt in situ characterization techniques such as synchrotron radiation and nano-CT to construct time-resolved models that are capable of capturing hydration gradients at interfaces.

(2) Low-temperature curing effects

Low-temperature environments are common in cold-region mining areas, where freezing processes exert dual effects on pore structure and hydration reactions (Figure 6a,b). Under freezing conditions, ice formation can temporarily fill pores and provide additional interfacial bonding, enabling limited early-age load-bearing capacity. However, hydration

kinetics are significantly inhibited, resulting in a lower content of hydration products, higher porosity, delayed strength development, and, in some cases, enhanced ductility [85].

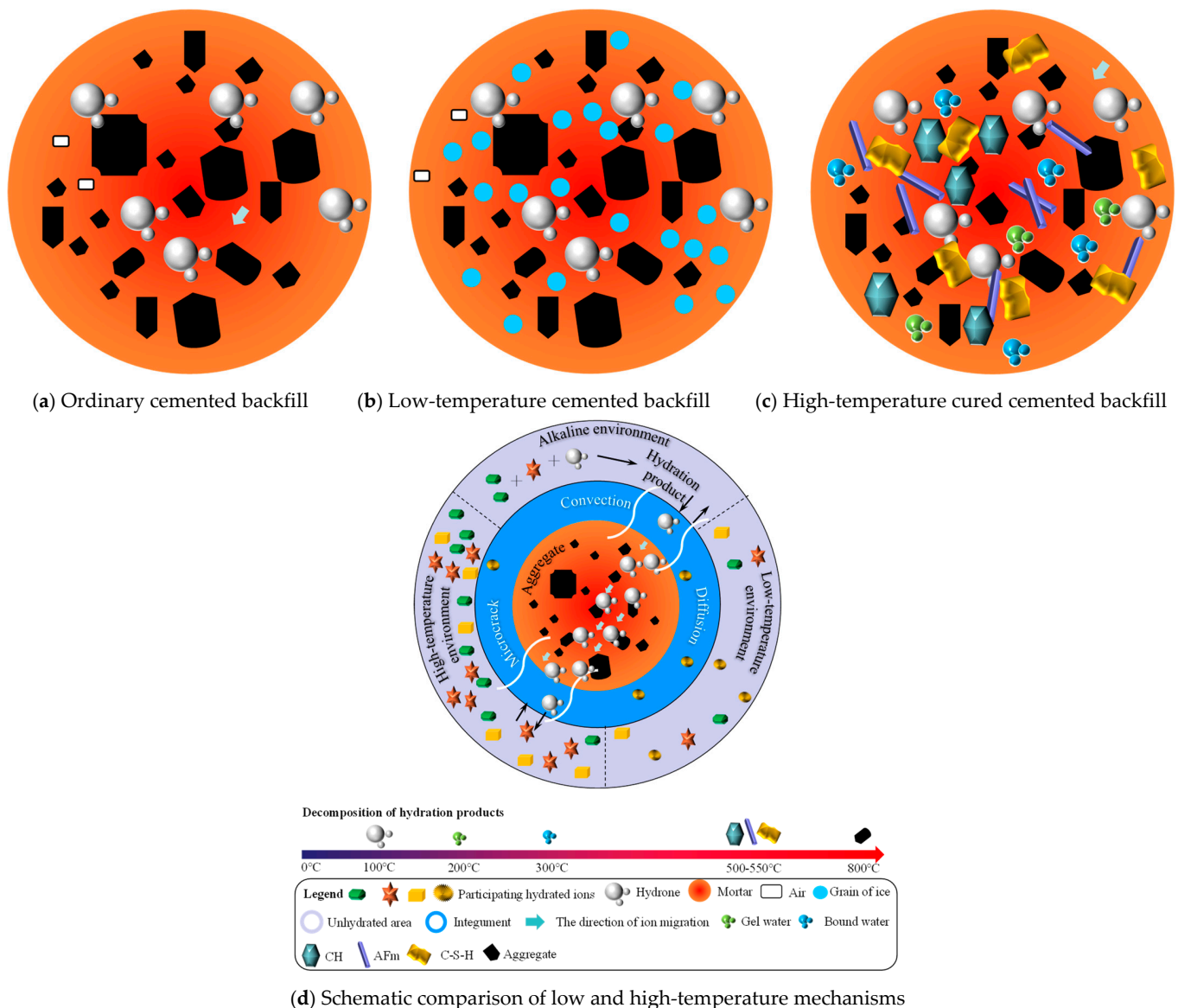


Figure 6. Schematic representation of temperature-dependent strength mechanisms of backfill.

Current studies largely rely on macroscopic UCSs and moisture measurements, with limited insights into ice migration, interfacial failure modes, or microcrack evolution under freeze–thaw cycling. Future research should incorporate low-temperature SEM, CT imaging, and multi-field coupled simulations to reveal mechanisms underpinning true micro-damage.

(3) High-temperature curing effects

High-temperature curing is considered one of the most effective environmental measures for enhancing early-age strength (Figure 6a,c). Elevated temperatures markedly shorten the induction period, accelerate gel deposition, and improve structural densification [86]. However, existing evidence indicates that temperature primarily affects the reaction rate rather than the fundamental types of hydration products formed [87].

Although high-temperature curing enhances the early-age strength, its effects on microcrack initiation, long-term pore rearrangement, and durability remain insufficiently understood, with most research confined to short-term observations. Future studies should focus on its influences on the fracture toughness, interfacial bonding, and long-term microstructural stability.

(4) Thermal damage under extremely high temperatures

Extreme thermal events such as fires or explosions can induce rapid evaporation of free water, gel water, and structural water, accompanied by the decomposition of C–S–H, AFt, and $\text{Ca}(\text{OH})_2$. This leads to the characteristic strength pattern of “slight increase at $\sim 200^\circ\text{C}$ and severe degradation at $\sim 400^\circ\text{C}$ ” [88]. This reflects a transition of the structural skeleton from dense to loose, a sharp increase in the pore connectivity, and the intrinsic nature of thermally driven structural deterioration.

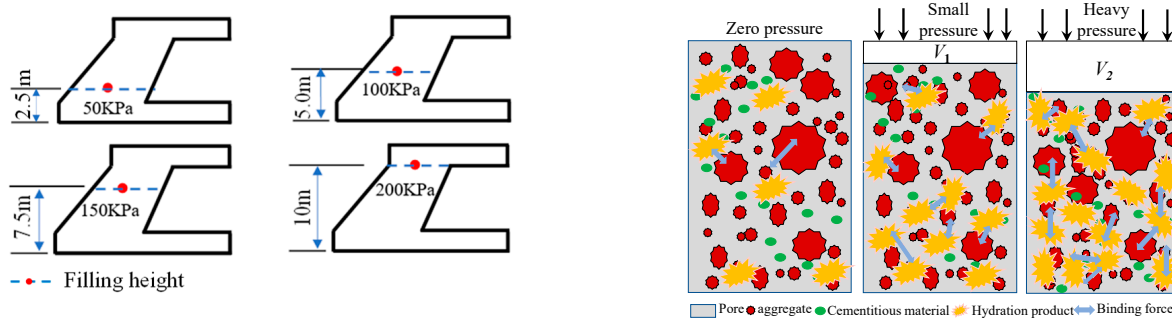
Mechanistic understanding remains limited: systematic quantification of high-temperature decomposition products, pore structure reconstruction, and residual strength relationships is sparse, as are molecular-dynamics-based validations of the mechanisms of thermal degradation. Future work should develop coupled models integrating thermal decomposition, reverse reactions, and mechanical degradation to support the design of high-temperature-resistant materials.

(5) Distinct mechanisms between the initial temperature and high-temperature curing

Although both temperature ranges fall within the routine working interval of $20\text{--}50^\circ\text{C}$, their mechanisms of action are fundamentally different (Figure 6d). The initial temperature affects the match between early hydration reaction rates and ion transport capability, whereas high-temperature curing provides continuous thermal input that sustains deep hydration over time—representing a “continuous driving effect.” This temporal sequencing plays a decisive role in microstructural evolution, yet most existing strength models adopt static temperature assumptions, failing to characterize the non-steady state of real mining environments. Therefore, future work should develop dynamic temperature-coupled models that are capable of characterizing the full “initial temperature–curing temperature–age” evolution sequence, thereby constructing a strength-prediction framework more consistent with engineering practice.

4.2. Stress Field

Stress is a key environmental variable regulating the establishment of effective stress, the evolution of pore structure, and crack development in cemented backfill. Its influence can be interpreted as shaping the mechanical behavior at different stages by affecting pore-water pressure dissipation, self-weight consolidation, and the load transfer path (Figure 7).



(a) Filling height and corresponding pressure

(b) Schematic representation of the function of pressure curing

Figure 7. Schematic representation of the mechanism of action of pressure curing.

(1) Pore-water pressure

During the early curing stage, pore-water pressure governs hydration kinetics, ion diffusion capacity, and the formation of an effective stress network, making it the dominant variable controlling the evolution of early-age strength. The generation of hydration products consumes free water, gradually transforming pore-water pressure into effective stress, thereby promoting skeletal compaction and enhancing load-bearing capacity. However, excessively rapid local hydration may produce a dense obstruction layer on particle surfaces, restricting moisture migration and generating internal “unhydrated cores,” which ultimately limit the development of strength [89].

Although empirical models describing pore-pressure decay with curing age have been proposed, the coupled mechanisms acting among hydration rate, seepage-driven transport, and effective stress reconstruction remain to be fully quantified. Future studies should incorporate in situ pore-pressure monitoring and multiphysics coupled simulations to evaluate the feedback relationship between the pore-pressure evolution and structural densification, thereby supporting process control and accurate prediction during early curing.

(2) Self-weight consolidation stress

As the pore-water pressure dissipates, self-weight consolidation and lateral confinement from surrounding rock become the primary drivers of sustained compaction in the backfill. Self-weight-induced drainage and consolidation can significantly enhance the particle contact density and interfacial bonding, resulting in in situ backfill strength that is generally larger than that of laboratory-prepared specimens [90]. However, consolidation under geostatic stress is affected by slurry rheology, filling height, drainage conditions, and surrounding constraints, leading to pronounced spatial heterogeneity.

Current studies are mostly based on core sampling comparisons or unidirectional loading tests, which cannot fully capture the coupled evolution between pore structure and hydration kinetics during consolidation. Future work should integrate long-term field monitoring, 3D consolidation simulations, and multiscale pore-structure characterization to develop quantitative models describing self-weight consolidation effects on the strength development, providing a theoretical basis for strength prediction under different filling heights and engineering conditions.

(3) Late-stage service loads

Once the backfill enters the service phase, it is subjected to mining-induced disturbances and ground pressure, and its stress state transitions to a damage-dominated process characterized by the initiation, propagation, and coalescence of cracks. Fatigue effects, interfacial weak zones, and initial defects become progressively activated under sustained loading, eventually evolving into key factors controlling the failure mode [91]. Studies have shown that variations in the crack inclination and weak-interface distribution significantly affect the pathways of energy accumulation and dissipation, thereby determining failure patterns and the residual strength (Figure 8) [92].

However, current research mainly focuses on macroscopic descriptions from uniaxial or triaxial testing, with limited understanding of the microscopic mechanisms linking initial defect structures, energy evolution, and damage pathways. A unified damage model suitable for analyzing engineering-scale stability is still lacking. Future studies should develop multi-field in situ monitoring techniques—such as acoustic emission (AE), CT, and digital rock analyses—to establish multiscale crack evolution models and construct strength degradation prediction methods tailored to strip-filling and longwall backfilling conditions, thereby supporting safety assessment under mining-induced stresses.

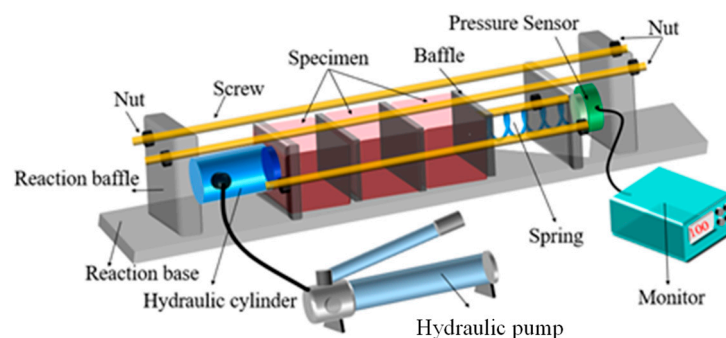


Figure 8. Schematic representation of the pressure-curing device (Replotted based on data from [93]).

4.3. Chemical Factors

The chemical environment profoundly affects the pore-structure evolution, interfacial behavior, and long-term mechanical stability of cemented backfill by altering solution composition, ion migration, and hydration reaction pathways. Its influence is primarily manifested through internal and external chemical attack. Due to differences in system composition, cement-based and solid-waste-based binders exhibit distinct sensitivities and reaction pathways under chemical exposure [86,87].

(1) Internal and external chemical attack

Internal chemical attack is commonly induced by the oxidation of sulfides present in sulfur-bearing tailings or solid wastes. Continuous generation of sulfate ions leads to the precipitation of gypsum and high-sulfur ettringite. While a local filling effect may temporarily enhance early-age strength, ongoing reactions generate expansive stresses that drive microcrack propagation, resulting in the characteristic “initial strengthening followed by degradation” behavior [86].

External chemical attack is jointly controlled by the chemical composition of mine water, seepage flux, and temperature. Sulfate and chloride ions interact with hydration products during long-term permeation, potentially causing interfacial softening, crystallization-induced expansion, and structural loosening [88]. The deterioration trend intensifies over time as ion accumulation progresses. Recent sulfate attack models generally describe this process as a sulfate transport–reaction–expansion–damage coupling mechanism, in which SO_4^{2-} ingress, gypsum/ettringite formation, expansive stress, and crack-induced diffusivity enhancement jointly control long-term strength degradation.

Importantly, there is no consensus regarding whether sulfate or chloride exposure inevitably leads to strength reduction. Some studies indicate that moderate ion concentrations may promote gel formation and improve interfacial densification, producing limited strength gains at specific curing ages. However, a larger body of evidence implies that long-term ion accumulation ultimately governs structural deterioration. The net effect strongly depends on the ion concentration, hydration stage, seepage conditions, and the type of binder system involved.

(2) Differences between cement-based and solid-waste-based systems

In cement-based systems, chemical attack typically manifests as expansion and structural damage. In contrast, in slag-rich or multicomponent solid-waste-based systems, sulfate exposure may, in some cases, enhance the dissolution of latent reactive phases and improve gel stability. Existing studies remain largely empirical, lacking a unified theoretical framework capable of describing the competitive mechanisms among ion transport, reaction kinetics, and crack evolution (Table 7) [89,90].

This gap represents both a fundamental bottleneck in understanding chemically induced degradation and a key challenge for predicting long-term durability and guiding material design under high-salinity mine-water conditions.

Table 7. Main hydration reactions and mixed sulfate reactions of different cementitious materials.

	Portland Cement	Slag
Hydration reaction	$C_3S + nh \rightarrow C-S-H + (3-x)CH$	$CaO + H_2O \rightarrow Ca(OH)_2$
	$C_2S + mh \rightarrow C-S-H + (2-x)CH$	$SiO_2 + m_1Ca(OH)_2 + nH_2O \rightarrow$
	$C_3A + 27H \rightarrow C_3AH_6 + C_2AH_8$	$m_1CaO \cdot SiO_2 \cdot nH_2O$
	$C_4AF + 2CH_2 \cdot 6CaSO_4 \cdot 2H_2O + 50H \rightarrow$ $2C_3(A \setminus F) \cdot 6CaSO_4 \cdot 32H_2O$	$Al_2O_3 + m_2Ca(OH)_2 + nH_2O \rightarrow$ $m_2CaO \cdot Al_2O_3 \cdot nH_2O$
Reaction with sulfate	$Ca(OH)_2 + SO_4^{2-} + H_2O \rightarrow CaSO_4 + H_2O$	
	$Ca(OH)_2 + C-S-H + MgSO_4 + H_2O \rightarrow$ $CaSO_4 \cdot 2H_2O + Mg(OH)_2 + SiO_2 \cdot x H_2O$	$3Ca \cdot Al_2O_3 \cdot 6H_2O + 3CaSO_4 + 26H_2O \rightarrow$ $3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O$
	$3CaO \cdot Al_2O_3 \cdot Ca(OH)_2 \cdot (12-18) H_2O$ $+ SO_4^{2-} \cdot H_2O + H_2O \rightarrow$ $3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O$	$4CaO \cdot Al_2O_3 \cdot Fe_2O_3 + 3CaSO_4 + 36H_2O \rightarrow$ $3CaO \cdot [xAl_2O_3 \cdot (1-x)Fe_2O_3] \cdot 3CaSO_4 \cdot 32H_2O +$ $Ca(OH)_2 + 2xFe(OH)_3 + (2-2x)Al(OH)_3$
	$Ca(OH)_2 + C-S-H + SO_4^{2-} + H_2O \rightarrow$ $3CaSiO_2 \cdot CaCO_3 \cdot CaSO_4 \cdot H_2O$	
	$C_3A \cdot 3CaSO_4 \cdot 32H_2O + 2NaCl \rightarrow$ $C_3A \cdot 3CaCl_2 \cdot 10H_2O + 2(CaSO_4 \cdot 2H_2O) +$ $2Na^+ + SO_4^{2-} + 18 H_2O$	$Al_2O_3^{2-} \cdot 4CaO + 2NaCl + 11 H_2O \rightarrow$ $3CaO \cdot Al_2O_3 \cdot CaCl_2 \cdot 10H_2O + 2Na(OH)_2$

4.4. Seepage Effects

Seepage can significantly influence the strength development and long-term stability of cemented backfill by affecting pore-water migration, fracture connectivity, and ion transport. As a porous medium that readily develops cracks under loading, cemented backfill exhibits seepage behavior with significant time dependence and structural sensitivity. Existing studies mainly focus on three scenarios: intact backfill, fractured backfill, and in situ seepage behavior [91].

(1) Intact cemented backfill

In an intact cemented backfill, seepage is jointly governed by particle gradation, pore structure, and the spatial distribution of hydration products. Studies show that the permeability coefficient is highly sensitive to porosity, aggregate heterogeneity, and the degree of hydration, evincing strong structural dependence. Temperature gradients and variations in pore-water pressures further influence moisture migration and pore closure processes, making them crucial external variables controlling early hydration kinetics [92].

However, quantitative understanding of the bidirectional feedback between seepage and hydration remains limited. Seepage affects hydration, while hydration alters permeability—yet this iterative process lacks a systematic modeling framework, representing one of the major gaps in the knowledge around the state-of-the-art.

(2) Fractured cemented backfill

Once natural or stress-induced fractures form, seepage behavior transitions from pore-dominated to fracture-dominated flow, exhibiting geometric amplification effects. Extensive experimental and discrete element modeling/computed tomography (CT) studies indicate that fracture aperture, connectivity, and fractal characteristics determine the seepage pathways; seepage pressure can significantly alter the rates of crack propagation and damage accumulation patterns; stress loading induces cyclic crack opening and closure, giving rise to the characteristic “seepage–force-chain disturbance” phenomenon [92].

Although previous research clarified the fundamental seepage laws governed by fractures, quantitative predictions of the crack evolution under coupled stress–seepage–damage conditions remain inadequate, limiting their applicability for the analysis of strength degradation in complex mining environments.

(3) In situ seepage behavior

In situ seepage is jointly affected by groundwater recharge, mining-induced disturbances, and layered structural features. Layered interfaces—typically loose and discontinuous—serve as primary seepage channels. Their controlling role often exceeds that of the intrinsic pore structure and can even become the main factor driving long-term strength deterioration. However, current research largely relies on simplified homogeneous models, with insufficient characterization of seepage fields along layered weak planes [93]. Although in situ monitoring techniques such as TDR and fiber-optic sensing show considerable promise, their systematic application in cemented backfill remains limited.

Overall, seepage effects permeate the entire life cycle of cemented backfill, from early curing to the crack evolution and long-term service. The underlying mechanisms exhibit typical multi-field coupling characteristics. Major limitations in current research include: the lack of systematic quantification of the bidirectional regulation between seepage and hydration kinetics; the absence of cross-scale predictive models for coupled stress–seepage–damage evolution; insufficient investigation of layered interface–controlled seepage behavior in field conditions. Future efforts should focus on developing integrated models capable of simultaneously describing hydration, damage evolution, and seepage behavior to support durability prediction and the assessment of structural safety under complex groundwater environments.

4.5. Multi-Field Coupling

During underground service, cemented backfill is simultaneously subjected to the effects of environmental temperature, humidity, stress, seepage, and chemical composition. Its strength evolution therefore arises from the coupled regulation of hydration reactions, transport processes, and mechanical responses, rather than being governed by any single physical field [33,94], as illustrated in Figure 9 and Table 8.

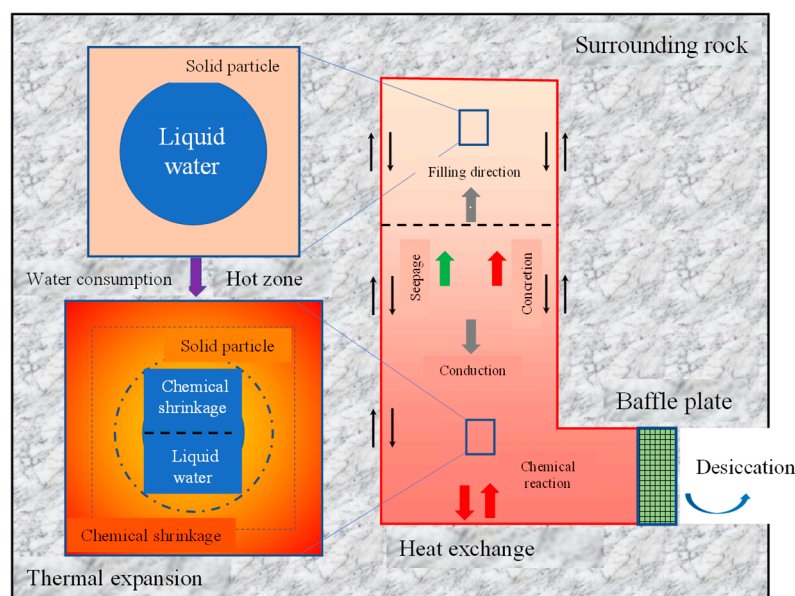


Figure 9. Multi-field coupling diagram (Replotted based on data from [63]).

(1) Multi-field coupling behavior in laboratory studies

Through controlled drainage conditions, temperature histories, and chemically partitioned experiments, existing studies have obtained systematic datasets describing the evolution of porosity, saturation, moisture content, and thermal conductivity with the curing age and filling height. These results clarified the fundamental pattern in which

moisture migration, thermal effects, and chemical reactions jointly drive pore-structure reconstruction. Such experiments provide strong evidence for mechanisms including “thermal fields influencing dissolution–precipitation rates,” “seepage regulating hydration progression,” and “chemical environments modifying gel structure” [94].

However, most experiments remain focused on macroscopic indicators and struggle to capture time-resolved microstructural changes at interfaces or localized thermo–hydraulic effects, leaving current understanding of coupling mechanisms largely at a phenomenological level.

(2) Development of multiphysics coupling models

Thermal–hydraulic–mechanical–chemical (THMC) models, constructed based on COMSOL Multiphysics 5.0 and generalized Biot porous media theory, can simultaneously characterize heat conduction, saturated/unsaturated seepage, chemical reaction kinetics, thermally induced expansion, and suction evolution. These models are capable of simulating strength–evolution pathways of coal gangue–fly ash–cement systems under complex environmental conditions. Their predictions align well with laboratory tests, analytical solutions, and field monitoring data (e.g., pore–water pressure and temperature profiles), showing strong practical applicability [15,95].

Nevertheless, the representation of pore evolution, interfacial reactions, and crack initiation remains relatively coarse. Most models cannot realistically capture the localized response of the ITZ or layered weak planes.

(3) Mechanistic enhancement and expansion of governing equations

Overall, multi-field coupling studies have progressed from validation-oriented simulations to mechanistic interpretation. Yet significant limitations remain in parameter acquisition, characterization of the interfacial process, and identification of coupling sequences. Future research should, as a matter of urgency, aim to establish mechanism-driven models centered on micro-scale reactions and interfacial evolution, while incorporating in situ monitoring techniques for dynamic model calibration [96]. Such advancements are essential for achieving reliable prediction of backfill performance under complex and variable conditions of real underground environments. Although these environmental prediction models can reproduce strength evolution under specific conditions, most remain calibrated by limited laboratory data and single-field assumptions, which restricts their applicability under coupled temperature–seepage–chemical–stress conditions.

Table 8. Typical cases of strength prediction for cemented backfill.

No.	Raw Materials	Types of Fields	Parameter Settings	Research Focus	Main Conclusions	Reference
1	42.5R ordinary Portland cement, tailings	Temperature	20, 30, 40, 50, 60 °C,	Investigated the effect of the curing temperature on the mechanical properties of CTB through uniaxial compression.	UCS follows a quadratic trend; 40 °C showed maximum hydration, and a unified temperature–time damage model was developed.	[83]
2	Coal gangue, fly ash, 42.5 ordinary Portland cement	Temperature	20, 35, 50 °C	Investigated the effect of the curing temperature on the triaxial mechanical properties of cemented backfill.	Peak strength and dilatancy stress follow a nonlinear pattern with temperature. The Mogi–Coulomb criteria best represent strength properties.	[84]

Table 8. Cont.

No.	Raw Materials	Types of Fields	Parameter Settings	Research Focus	Main Conclusions	Reference
3	Modified magnesium slag, fly ash, aeolian sand	Temperature	20, 30, 40 °C	Investigated the mechanical and failure behavior of modified magnesium slag-fly ash cemented paste backfill under varying curing temperatures using UCS, AE, and SEM.	Strength and energy increased with temperature, peaked at 40 °C, but thermal stress weakened later-age strength.	[85]
4	Monofilament polypropylene, quartz tailings	Temperature	20, 35, and 45 °C	Investigated curing-dependent shear behavior of FR-CPB reinforced with polypropylene fiber under geothermal conditions.	At 45 °C, cohesion, stiffness, dilation angle, and brittleness index increased by ~62%–68%; friction angle remained stable.	[86]
5	Modified magnesium slag-based cementitious material, fly ash, coal gangue	Temperature (Add flocculant)	2 °C, 20 °C, and 50 °C; containing 0, 55, 75, and 85 g/t flocculants,	Investigated the effects of the curing temperature and flocculant dosage on fluidity, compressive strength, and microstructure of CPB.	Yield stress and viscosity increased with higher temperature and flocculant dosage; 28-day UCS was enhanced by temperature, but decreased with dosage.	[87]
6	Tailings,	Temperature	−1, −6, −12 °C	Studied the frost damage effect on SPD, analyzing temperature, mechanical performance, and microstructure evolution.	Freezing caused significant UCS loss; 1-day pre-cured SPD at −12 °C shows 56% strength loss. Silica fume improved UCS by 25.3%.	[88]
7	Tailings, cement	Stress (Consideration of Drainage)	Stress: 300 kPa, 600 kPa; drained, no drainage	Investigated the strength difference of backfill under various curing stress and drainage conditions using sensors for parameter monitoring.	Stress-drainage curing conditions reduced porosity, increased the pore-water pressure, and improved strength; electrical conductivity followed a decreasing trend.	[89]
8	Copper tailings, 42.5R Portland cement	Stress	Curing stresses (0 kPa—witness, 180 kPa, 360 kPa, and 540 kPa	This study investigated the impact of various curing stresses on the physico-mechanical properties of CTB materials over a curing period of up to 28 days.	Curing stress from 0 to 540 kPa improved the strength of CTB, reduced porosity, and increased suction; a strong power function existed between suction and strength.	[89]
9	Ordinary Portland cement Type I (PCI), tailings	Stress	Drainage, curing stress, curing time, and filling rate	This study investigated the strength and deformation behavior of CPB under various loading conditions and curing scenarios.	Curing stress, drainage, filling rate, and time influenced the strength of CPB; curing stress accelerated hydration, aiding in strength gain.	[91]
10	Slag, co-fired ash, crude coal gangue, fine coal gangue	Chemical	SO ₄ ^{2−} , Cl [−] and Mg ²⁺	This study explored the durability and erosion mechanism of biomass-coal mixed combustion ash geopolymer backfill under compound salt erosion.	After 30 wet–dry cycles, biomass-coal mixed combustion ash geopolymer backfill showed 0.93% mass loss, UCS decreased by 33.2%, and gypsum, Friedel’s salt, Aft, and M-S-H formed.	[92]
11	Coal gangue, fly ash, cement	Chemical	Solution type	This study explored the deformation, strength, and AE of gangue cemented backfill in various environments over 360 days.	At 360 days, compressive strength: water > air > H ₂ SO ₄ > H ₂ SO ₄ + load; strength decreased with a larger specimen size.	[97]

Table 8. Cont.

No.	Raw Materials	Types of Fields	Parameter Settings	Research Focus	Main Conclusions	Reference
12	Silicate tailing, slag, alkali activators, distilled water	Chemical	Sulfate concentration (ppm) 0, 5000, 15,000, and 25,000	This study investigated the behavior of alkali-activated slag carbonated CPB under internal sulfate attack with various activator ratios.	High content of sulfate increased the yield stress and viscosity; CPB with a high SS/SH ratio showed a weaker sulfate resistance.	[98]
13	Tailings, PCI, distilled water	Chemical	Sulfate concentration of 0, 5000, 15,000, and 25,000 ppm	This study examined the sulfate effect on early-age strength and self-desiccation of CPB at different sulfate concentrations.	Sulfate reduced the CPB strength and self-desiccation, with higher sulfate concentrations (up to 25,000 ppm) showing stronger effects.	[99]
14	Tailings, mixing water, and a one-part alkali-activated slag binder	Chemical	NaCl, CaCl ₂ , and MgCl ₂ with different Cl [−] concentrations (0.50, 0.77, and 1.0 mol/L)	This research explored the effects of chloride salts on the strength and hydration behavior of CTB with alkali-activated slag binder.	Chloride salts reduced the CTB strength by 3.2%–25.0%, with NaCl causing decalcification and increased porosity.	[100]
15	Silica tailings, PCI, distilled water	Chemical + Temperature coupling	different sulfate contents (0 ppm, 5000 ppm, 15,000 ppm, and 25,000 ppm); temperatures (2 °C–35 °C)	Investigated the rheology of CPB under the combined effects of the sulfate content, temperature, and time using various measurements.	Viscosity increased significantly; yield stress slightly increased; the sulfate effect was offset by high temperature and time.	[101]
16	Coal gangue, coal gangue, FA, ordinary Portland cement	Chemical-Temperature coupling	Solution concentration (5%, 10%, 20%); temperature (25, 32.5, 40); solution concentration (NaCl, Na ₂ SO ₄ , MgCl ₂)	Studied the strength deterioration of geopolymer cemented coal gangue-fly ash backfill under various temperatures, salt concentrations, and solution types.	UCS increased by 164.9% in 20% Na ₂ SO ₄ ; Mg ²⁺ erosion enlarged pores to 23.499%, reducing density and strength.	[33]
17	Synthetic silica tailings, Portland cement	Thermal(T)-hydraulic(H)-mechanical(M)-chemical(C) coupling	20 °C, field temperature; stress-free, field stress; sulfate in mixing water (ppm) (C) 0, 15,000	Investigated pore-water pressure in sulfate-bearing CPB-PES under THMC field conditions and varied drainage scenarios.	High sulfate increased initial pore-water pressure; THMC curing accelerated hydration and drainage, reducing sulfate effects.	[94]
18	Coal gangue, fly ash, cement, and additive	Seepage-stress coupling	seepage pressure (MPa): 0, 0.4, 0.8; effective stress (MPa): 0.2, 0.6, 1.0	Studied creep behavior of cemented coal gangue-fly ash backfill (CGFB) under seepage-stress coupling and established a seepage-based creep damage model.	Long-term strength was 56–75% of instantaneous strength; higher seepage pressure increased the creep rate and shortened the acceleration onset.	[95]
19	Coal gangue, fly ash, cement	THMC coupling	\	Developed a THMC coupling model to analyze CGFB behavior under thermal, hydraulic, mechanical, and chemical effects.	Model predictions aligned with three case studies, accurately characterizing CGFB under THMC loads for better structural design.	[11]
20	Tailings, water, and binder	THMC coupling	\	Established a THMC-coupled model to simulate CPB behavior from early to advanced ages under multiphysics processes.	Model accurately predicted the strength, porosity, and deformation of CPB; validated by laboratory and field tests with strong agreement.	[96]

5. Structural-Level Influencing Factors

5.1. Strength-Weakening Effect of Layered Interfaces

5.1.1. The Number and Inclination of Layered Interfaces

With respect to layered interfaces, laboratory UCS tests show that strength decreases as the number of interfaces increases. The 30.2%–51.8% reduction shown in Figure 10 was obtained from small cylindrical cemented backfill specimens prepared with tailings, cement, and water, typically 50 mm in diameter and 100 mm in height, cured for 28 d and tested under uniaxial compression with free lateral boundaries. Therefore, this range represents a laboratory-scale weakening effect under specific material and boundary conditions, rather than a universal field-scale coefficient [102,103]. Layered interfaces are the most typical structural heterogeneity in in situ cemented backfill, formed jointly by staged grouting, particle deposition, and slurry flow. They generally show weak bonding and concentrated porosity, resulting in structurally vulnerable planes. During loading, these interfaces significantly alter stress-transfer paths, making cracks more prone to initiation and propagation in their vicinity. Hence, they are key factors governing the strength reduction of cemented backfill.

(1) Number of layered interfaces

As more weak planes are introduced, stress more readily concentrates at the interface tips during early loading, causing cracks to propagate along the interfaces at the initial stage. This leads to simultaneous reductions in overall stiffness and peak strength. This weakening trend is widely observed across different loading paths, types of solid waste, and specimen scales, showing the universality of interface-induced degradation [104].

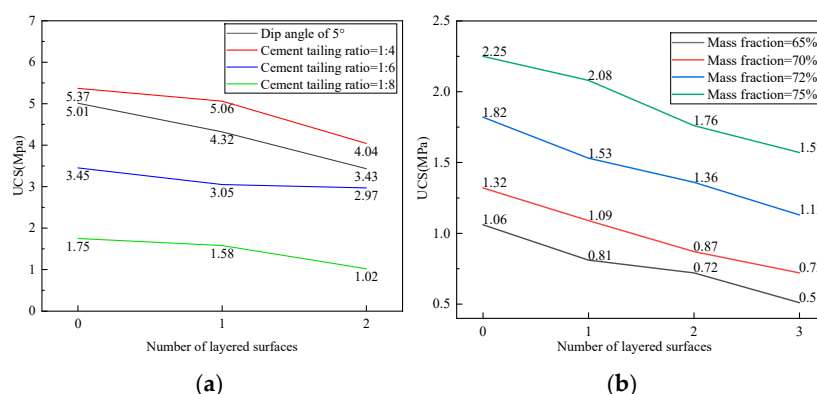


Figure 10. Effects of the number of layered interfaces on the strength of cemented backfill. (a) Different cement-sand ratios at 0° and 5° (fixed ratio) (Replotted based on data from [103,105]); (b) Different mass fractions (Replotted based on data from [104]).

(2) Inclination of layered interfaces

Regarding interface inclination, strength exhibits a distinct nonlinear response to the change in angle. Numerous laboratory tests and discrete element modeling simulations indicate that within the small-angle range of 0–15°, layered interfaces are nearly aligned with the major compressive stress direction, making interfacial sliding more likely; thus, strength decreases continuously with increasing angle, typically by 43.3%–50.6% [25,105,106], as illustrated in Figure 11. When the inclination increases to 15–60°, the interface gradually deviates from the main shear-band direction, the contribution of sliding diminishes, and matrix-controlled failure becomes more dominant. Correspondingly, the strength–angle relationship shows a characteristic U-shaped trend. Failure patterns also shift from interfacial sliding to the combined matrix–interface “X-shaped shear failure” mode [107].

(3) Microcrack development

From the perspective of crack evolution, layered interfaces serve as primary zones for the crack initiation and propagation [108]. During loading, microcracks first appear at interface tips, then extend along the interface, and subsequently interact with matrix cracks in the pre-peak stage, ultimately forming a fully connected failure plane. Analyses of AE, electromagnetic radiation, and energy dissipation consistently show that a higher number of interfaces and smaller inclination angles lead to earlier crack initiation, lower energy dissipation, and greater susceptibility to brittle instability. Some researchers further examined the effect of interface roughness, finding that rougher interfaces delay the onset of failure and lead to higher strength.

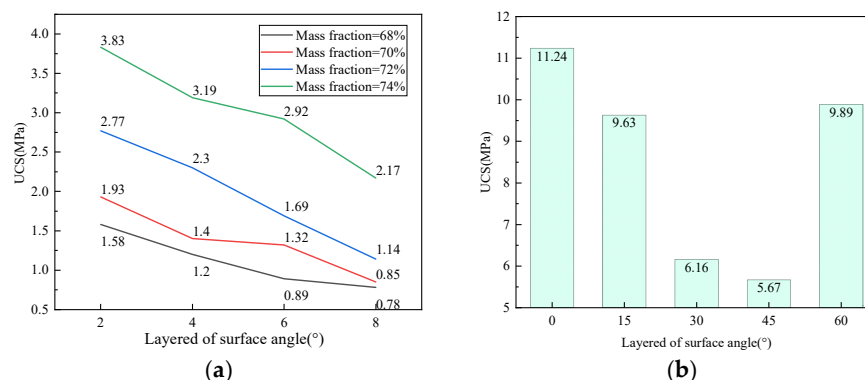


Figure 11. Effects of the angle of layered interfaces on the strength of cemented backfill. (a) 2–8° (Replotted based on data from [107]); (b) 0–60° (Replotted based on data from [108]).

5.1.2. Other Influencing Factors

(1) Effect of the filling interval time

The interval time between successive filling stages determines the continuity of interfacial hydration. Numerous studies confirmed that prolonged intervals hinder the formation of hydration products at the interface and reduce the ability of gel networks to grow across the interface, resulting in weakened bonding strength and increased susceptibility to the formation of initial microcracks. Although Cao et al. [17] reported limited changes in overall strength at 60 days, the early-age response is significantly more sensitive. Since the interface is very vulnerable to interruption of the hydration reaction during the initial setting stage, the interval time exhibits a pronounced time-dependent strengthening effect on the structural integrity.

(2) Effect of the intermediate-layer height

The height of the intermediate layer can affect the volume fraction of weak regions and is a key parameter controlling the degradation of structural-level strength. Wang et al. [109] found that when a low-strength material was used as the intermediate layer, increasing its height enlarged the volume of the weak zone, causing stress to concentrate more readily in this region during loading and triggering failure. This indicates that the structural weakening caused by layering depends not only on interface properties but also on the proportion of weak material. Therefore, the “volume fraction of weak layers” should be considered an essential design index for layered structures.

(3) Effects of the binder–aggregate ratio and related factors

Material factors such as the solid concentration and binder–aggregate ratio can significantly enhance the weakening effects induced by the interval time and intermediate-layer height. At lower solid concentrations, delayed setting and insufficient early-age hydration make the interface more prone to loosening, increasing the sensitivity of layered interfaces to interval time. When the binder–aggregate ratio is low, strength differences

between layers become more pronounced, rendering strength degradation due to changes in intermediate-layer heights more significant. These observations show a synergistic coupling between material factors and structural parameters, jointly controlling the mechanism of formation of layered interfaces and their effects on overall strength [105]. Other researchers examined layered backfill strength, considering prefabricated fractures [110], cyclic loading and unloading [106], soft interlayers [111], triaxial confinement [112], and dynamic loading conditions [113].

Overall, previous research has elucidated the weakening effects of interface number, inclination, and related parameters, confirming that “layered interfaces” are major contributors to load-bearing degradation in cemented backfill. However, current studies remain largely confined to single-mechanical-field conditions and lack a comprehensive exploration of long-term interface evolution under coupled seepage, chemical, and thermal environments. Most research focuses on describing weakening phenomena, while effective strategies for actively enhancing interface performance through material design or process optimization remain limited.

Future efforts should aim to develop multi-field coupled experiments and cross-scale studies to reveal the mechanisms underlying the damage evolution of layered interfaces under complex conditions. Additionally, new cementitious materials, interface-enhancing admixtures, and intelligent grouting technologies should be explored to promote a transition from passive layering to actively controlled structural performance in cemented backfill systems.

5.2. Size Effects

To strengthen the generality of the size-effect discussion, evidence from global backfill studies was further compared. Reported laboratory, column, similar-stope, and in situ observations from different mining regions consistently indicate that the strength obtained from small homogeneous specimens cannot be directly transferred to field-scale backfill. Although the reported size-effect multipliers vary with binder type, aggregate gradation, curing condition, drainage path, and boundary constraint, these cases show a common trend: larger or field-scale backfill bodies exhibit stronger spatial heterogeneity, more pronounced weak interfaces, and greater sensitivity to sedimentation-induced structure. This cross-case evidence supports the interpretation that the field backfill should be treated as a structural body rather than a homogeneous material specimen.

Yilmaz et al. [9] reported that, for a given CPB recipe and curing time, in situ strength may be about two to four times higher than laboratory strength. This difference was attributed to field placement and boundary conditions, such as stope geometry, drainage, consolidation, stress state, arching, and shrinkage effects, rather than specimen size alone. Research has shown that the compressive strength of backfill exhibits a “first increasing, then decreasing” trend with increasing specimen size, reaching a peak of 19.85 MPa at a size of 70.7 mm, while the elastic modulus is positively correlated with the specimen size [114]. This observation coincides with the findings of Zheng Yuanxiang et al., who found that the peak stress on, and strain in, gangue-cemented backfilled pillars decrease exponentially with increasing height–diameter ratio [115].

The influence of the size effect on failure modes is particularly significant. As the specimen size increases, the failure pattern transitions markedly—from tensile splitting to X-shaped shear failure [116]. Zhao Yonghui et al. [117] further confirmed that smaller height–width ratios lead to more ductile behavior, with failure shifting from splitting to shear. Bin Guo et al. observed similar transitions from splitting to X-shaped conjugate shear failure [118]. Environmental conditions can also couple with size effects. Under

combined sulfate attack and wet–dry cycling, the size-effect coefficient of coal gangue concrete increases with longer exposure periods [119].

Regarding the damage evolution, backfill specimens of different sizes exhibit similar, but not identical, characteristics. Zhao Mengye et al. [115] found that under UCSs, different-sized backfill specimens share comparable energy evolution patterns, with elastic strain energy dominating before the peak stress is attained. Through monitoring AE, Zheng Yuanxiang et al. [114] revealed that when the height–diameter ratio exceeds 2.0, the failure mode of backfilled pillars shifts from global to localized failure. Zhao Yonghui et al. [117] also developed a damage model based on AE ringing counts and resistivity measurements.

Despite progress in understanding the size effect of cemented backfill strength, a considerable gap remains between current research and engineering demands. Existing studies largely focus on single environmental conditions, small-scale laboratory specimens, and limited mix proportions, with insufficient attention to multi-factor coupling, engineering-scale dimensions, and long-term performance. Furthermore, the universality and predictive accuracy of current theoretical models under complex conditions remain limited, restricting their applicability in engineering design and stability assessment. Size-effect models provide useful corrections for laboratory-to-field extrapolation, but they often treat scale as an independent geometric factor, while field-scale backfill size effects are coupled with sedimentation heterogeneity, layered interfaces, boundary constraints, and stress redistribution.

6. Conclusions and Research Opportunities

6.1. Conclusions

This review systematically elucidates the multiscale influencing mechanisms governing the strength development of cemented backfill and establishes a three-level analytical framework comprising the material, environmental, and structural levels. The key conclusions are as follows:

(1) Material level

Existing studies have revealed the micro-mechanisms associated with hydration products, ITZ, and particle–gel interactions. Optimization of aggregate gradation and synergistic activation of multi-type solid waste have emerged as key pathways through which to improve backfill performance. However, current material design still relies heavily on empirical mix proportions and lacks quantitative design methodologies based on particle packing theory and multiphase reaction kinetics.

(2) Environmental level

Coupled multiphysical fields—including temperature, stress, chemical conditions, and seepage—significantly affect the evolution of hydration and microstructural development. Research is transitioning from single-factor analysis toward multi-field coupling models, yet a unified theoretical framework capturing the dynamic interaction among environment–materials–time remains absent.

(3) Structural level

Layered structures, anisotropy, and size effects—formed through deposition segregation and staged filling—are the dominant factors controlling macroscopic mechanical behavior in mine backfills. Layered weak planes can reduce the compressive strength by 30.2%–51.8%, and the in situ strength is typically two to four times that of laboratory specimens, underscoring the limitations of homogeneous material theories in explaining engineering-scale behavior.

Overall, these findings indicate the necessity of shifting from a purely material-based constitutive perspective toward a multiscale, material–environment–structure coupling framework to better support strength prediction under complex engineering conditions.

6.2. Outlook

Despite substantial progress in understanding cemented backfill strength, significant challenges remain in bridging laboratory insights and engineering applications:

(1) Need for systematic material design methodologies

Although current research emphasizes solid waste utilization and interface regulation, it lacks a quantitative design system that integrates particle morphology, gradation, and reactivity. Future work should utilize material-genome concepts and machine learning to construct intelligent mapping relationships among solid waste types, mix proportions, and mechanical performance, enabling a shift from “empirical trial-and-error” to “performance-oriented” design. This direction is primarily experimental and data-driven (standardized datasets), supported by modeling/data analytics, and should be verified through engineering-scale implementation.

(2) Lack of unified theories for structure-dominated mechanisms

The effects of layered weak planes, inclined interfaces, and size factors remain largely phenomenological, with no predictive mechanical models applicable to engineering practice. It is necessary to develop strength and failure criteria based on structural parameters (e.g., layer inclination, weak-plane density, equivalent size) and construct quantitative models for structural responses. This direction is mainly modeling-oriented, requiring targeted experiments for parameter identification and field-scale validation.

(3) Discrete element modeling for aggregate packing and strength prediction

Advanced techniques such as the discrete element method (DEM) should be more systematically introduced to quantitatively characterize aggregate morphology and gradation, and to elucidate their regulatory effects on the particle packing structure, contact state, and the evolution of interfacial strength. On this basis, DEM-derived packing descriptors can be integrated with experimental strength data to establish a strength-prediction model grounded in particle packing theory, thereby enabling more precise, design-oriented control of backfill strength through optimization of gradation and aggregate-related parameters.

(4) Insufficient research on multi-field coupling and long-term performance

Current studies mainly focus on short-term, single-field effects, with limited understanding of the long-term coupled evolution among underground temperature–seepage–chemical–stress fields. Future research should incorporate in situ monitoring and digital-twin technologies to establish full life-cycle performance evolution models for assessing long-term stability. This direction requires coupled experiments and multiphysics modeling in parallel, with long-term in situ monitoring for calibration and validation.

(5) Lack of engineering-oriented standards and guidelines

Significant discrepancies between laboratory measurements and field performance remain. Currently, there are no strength testing standards or design guidelines tailored to heterogeneous backfill materials. Standardization of cross-scale testing methods and development of structure-based engineering design criteria are essential to support safe and reliable translation of theoretical findings into engineering practice. This direction is field-oriented, relying on in situ monitoring and engineering validation, supported by laboratory benchmarking and model-based checks.

Future research should focus on establishing a multiscale coupling theoretical framework that integrates material, environmental, and structural characteristics, developing intelligent material design and structural-response prediction models, and promoting the transition in cemented backfill concepts from “homogeneous material” to “engineered structural body.” Overall, future quantitative prediction should move from empirical fitting toward mechanism-based models that integrate material heterogeneity, environmental coupling, structural anisotropy, and scale-dependent failure. A simple predictive route can be derived from the proposed “Materials–Environment–Structure” framework. Laboratory

UCS can be used as the baseline strength and then corrected by environmental factors, such as temperature, seepage, stress, and chemical exposure, and structural factors, such as interface inclination, layering, anisotropy, and size effect. This provides a preliminary approach for converting laboratory material strength into field-scale structural strength, although further calibration with long-term field data is still needed.

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References

1. Saletnik, A.; Saletnik, B.; Puchalski, C. Coal as the world's dominant energy source and its role in the energy transformation and regulations of European Green Deal. *J. Environ. Manag.* **2025**, *392*, 126815. [[CrossRef](#)] [[PubMed](#)]
2. Lopez, G.; Pourjamal, Y.; Breyer, C. Paving the way towards a sustainable future or lagging behind? An ex-post analysis of the international energy agency's world energy outlook. *Renew. Sustain. Energy Rev.* **2025**, *212*, 115371. [[CrossRef](#)]
3. Dehkordi, M.M.; Nodeh, Z.P.; Dehkordi, K.S.; Salmanvandi, H.; Khorjestan, R.R.; Ghaffarzadeh, M. Soil, air, and water pollution from mining and industrial activities: Sources of pollution, environmental impacts, and prevention and control methods. *Results Eng.* **2024**, *23*, 102729. [[CrossRef](#)]
4. Magazzino, C.; Haroon, M.; Zeo, X. Greening the mines: Managing efficiency; environmental impact, and ecology in chinese mining regions. *Resour. Policy* **2025**, *103*, 105564. [[CrossRef](#)]
5. Tao, M.; Memon, M.B.; Yang, Z.; Jiskani, I.M.; Chalgri, S.R. Towards greener coal mining: A life cycle assessment model for small-scale underground operations. *Min. Metall. Explor.* **2024**, *41*, 3103–3118. [[CrossRef](#)]
6. He, W.; Liu, L.; Wei, B.; Wang, R.; Fang, Z.; Qu, H.; Zhuang, D.; Gao, Y.; Xia, L.; Wang, Z. Study on mechanical properties and toughness characteristics of fiber reinforced storage backfill after carbonation curing. *Structures* **2025**, *77*, 108996. [[CrossRef](#)]
7. Chen, Y.; Wang, C.; Wu, Z.; Lu, T.; Huang, Y.; Deng, Z.; Chen, G. Prediction of the strength evolution and environmental benefits of phosphogypsum-red mud-based cementitious backfill materials. *Miner. Eng.* **2026**, *247*, 110443. [[CrossRef](#)]
8. Chiloane, N.M.; Mulenga, F.K. Revisiting factors contributing to the strength of cemented backfill support system: A review. *J. Rock Mech. Geotech. Eng.* **2023**, *15*, 1615–1624. [[CrossRef](#)]
9. Yilmaz, E.; Belem, T.; Benzaazoua, M. Specimen size effect on strength behavior of cemented paste backfills subjected to different placement conditions. *Eng. Geol.* **2015**, *185*, 52–62. [[CrossRef](#)]
10. Bewick, R.P.; Elmo, D. Size effect and rock mass strength. *Can. Geotech. J.* **2025**, *62*, 1–18. [[CrossRef](#)]
11. Al-Moselly, Z.; Fall, M. Multiphysical testing of strength development of cemented paste backfill containing superplasticizer. *Cem. Concr. Compos.* **2024**, *154*, 105772. [[CrossRef](#)]
12. Liu, J.; Li, X.; Huan, T. Application status and prospect of backfill mining in Chinese coal mines. *J. China Coal Soc.* **2020**, *45*, 141–150. [[CrossRef](#)]
13. Yilmaz, E.; Fall, M. (Eds.) *Paste Tailings Management*; Springer Nature: London, UK, 2017. [[CrossRef](#)]
14. Behera, S.; Mishra, D.; Singh, P.; Mishra, K.; Mandal, S.; Ghosh, N.; Kumar, R.; Mandal, P. Utilization of mill tailings, fly ash and slag as mine paste backfill material: Review and future perspective. *Constr. Build. Mater.* **2021**, *309*, 125120. [[CrossRef](#)]
15. Wu, D.; Deng, T.; Zhao, R. A coupled THMC modeling application of cemented coal gangue-fly ash backfill. *Constr. Build. Mater.* **2018**, *158*, 326–336. [[CrossRef](#)]
16. Cui, L.; Holmberg, B. Multiphysics processes in the interfacial transition zone of fiber-reinforced cementitious composites under induced curing pressure and implications for mine backfill materials: A critical review. *Int. J. Miner. Metall. Mater.* **2023**, *30*, 2128–2150. [[CrossRef](#)]
17. Cao, S.; Song, W. Effect of filling interval time on the mechanical strength and ultrasonic properties of cemented coarse tailing backfill. *Int. J. Miner. Process.* **2017**, *166*, 62–68. [[CrossRef](#)]
18. Liu, H.; Zhang, J.; Zhou, N.; Guo, Y.; Li, B.; Yan, H.; Deng, X. Investigation of spatial stratified heterogeneity of cemented paste backfill characteristics in construction demolition waste recycled aggregates. *J. Clean. Prod.* **2020**, *249*, 119332. [[CrossRef](#)]

19. Nurizada, A.; Kirane, K. Induced anisotropy in the fracturing behavior of 3D printed parts analyzed by the size effect method. *Eng. Fract. Mech.* **2021**, *241*, 107304. [[CrossRef](#)]
20. Ghorbani, E.; Shahinfar, M.; Taheri, A. A review of the geological characterization, classification, modeling, and case studies of anisotropic rock masses. *Deep Resour. Eng.* **2025**, *2*, 100219. [[CrossRef](#)]
21. Ahrami, O.; Koupaei, H.J.; Ahangari, K. Determination of deformation modulus and characterization of anisotropic behavior of blocky rock masses. *Min. Sci. Technol.* **2024**, *9*, 116–133. [[CrossRef](#)]
22. Kong, L.; Guo, P.; Wan, J.; Liu, C.; Wang, J.; Chen, C. Detrital Zircon U-Pb Geochronology and Hf Isotopes of Mesoproterozoic Metasedimentary Rocks in Dabie Orogen and Its Geological Significance. *Earth Sci.* **2022**, *47*, 1333–1348.
23. Shahsavari, M.; Jafari, M.; Grabinsky, M. Simulation of cemented paste backfill (CPB) deposition through column experiments: Comparisons of field measurements, laboratory measurements, and analytical solutions. *Can. Geotech. J.* **2023**, *60*, 1505–1514. [[CrossRef](#)]
24. Qu, H.; Liu, L.; Suo, Y.; Zhu, M.; Wang, R.; Yang, P.; Xie, G.; Luo, Y.Y.; Liu, D. Failure behavior and fracture evolution mechanism of layered backfill considering dip angles. *Constr. Build. Mater.* **2024**, *416*, 135041. [[CrossRef](#)]
25. Kumar, D.; Mishra, A.; Kumar, S. Effect of interface geometric parameters on the mechanical properties and damage evolution of layered cemented gangue backfill: Experiments and models. *Constr. Build. Mater.* **2024**, *456*, 139248. [[CrossRef](#)]
26. Gencil, O.; Özgüler, A.T.; Güler, O.; Ustaoglu, A.; Hekimoğlu, G.; Sarı, A.; Emiroğlu, M.; Subaşı, S. Thermal energy storage and mechanical enhancement of cement composites containing PCM-impregnated and cement-slurry coated pumice aggregates. *J. Energy Storage* **2025**, *132*, 117847. [[CrossRef](#)]
27. Jiang, T.; Chen, B.; Bai, J.; Liu, B.; Chen, M. Improving mechanism for recycling efficiency of ceramic construction solid waste and properties of composite backfill based on aggregate particle size distribution. *Constr. Build. Mater.* **2024**, *436*, 136826. [[CrossRef](#)]
28. Wu, J.; Feng, M.; Mao, X.; Xu, J.; Zhang, W.; Ni, X.; Han, G. Particle size distribution of aggregate effects on mechanical and structural properties of cemented rockfill: Experiments and modeling. *Constr. Build. Mater.* **2018**, *193*, 295–311. [[CrossRef](#)]
29. Khandani, F.S.; Atapour, H.; Rad, M.Y.; Khosh, B. An experimental study on the mechanical properties of underground mining backfill materials obtained from recycling of construction and demolition waste. *Case Stud. Constr. Mater.* **2023**, *18*, e02046. [[CrossRef](#)]
30. Ji, Y.; Xie, L.; Xiao, J.; Zheng, Y.; Ma, S.; Pan, T. Mechanical properties and acoustic emission characteristics of microbial cemented backfill with various particle size distributions of recycled aggregates. *Constr. Build. Mater.* **2024**, *417*, 135269. [[CrossRef](#)]
31. He, Z.; Ju, F.; Xiao, M. Effects of aggregate size and carbon fiber content on piezoresistive responses of smart coal waste-based cemented paste backfill. *Constr. Build. Mater.* **2025**, *470*, 140562. [[CrossRef](#)]
32. Hou, Y.; Yin, S.; Wang, Y.; Yu, X.; Li, X.; Wang, L.; Yang, K.; Huang, X. Mechanical properties and damage evolution mechanisms of cemented backfill with tailored particle size range of coal gangue aggregates. *Process Saf. Environ. Prot.* **2025**, *198*, 107123. [[CrossRef](#)]
33. Cai, C.; Li, F.; Fan, S.; Yan, D.; Sun, Q.; Jin, H.; Shao, J.; Chen, Z.; Liu, M. Investigation on deterioration mechanism of geopolymer cemented coal gangue-fly ash backfill under combined action of high temperature and salt corrosion environment. *Constr. Build. Mater.* **2023**, *398*, 132518. [[CrossRef](#)]
34. Hou, Y.; Yin, S.; Wang, L.; Yang, K.; Yu, X.; Kou, P.; Wang, Y. Influence of mixing time and coarse aggregate content on the flowability, setting time, and mechanical properties of cemented backfill. *Constr. Build. Mater.* **2024**, *449*, 138513. [[CrossRef](#)]
35. Yaya, N.S.; Cao, S.; Yilmaz, E. Effect of 3D printed skeleton shapes on strength behavior, stress evolution and microstructural response of cement-based tailings backfills. *Constr. Build. Mater.* **2024**, *432*, 136699. [[CrossRef](#)]
36. Lazorenko, G.; Kasprzhitskii, A.; Yatsenko, E.A.; Li, W.; Chaudhary, S. Towards coal mining waste valorization: Gangue as resource for the production of geopolymer and related alkali-activated materials. *Green Technol. Sustain.* **2025**, *3*, 100205. [[CrossRef](#)]
37. Yadav, A.K.; Mishra, S.; Mishra, D.P. A detailed review study on utilization of mine and industrial wastes for backfill strengthening. *Arab. J. Geosci.* **2024**, *17*, 121. [[CrossRef](#)]
38. Cavusoglu, I. Slag substitution effect on features of alkali-free accelerator-reinforced cemented paste backfill. *Minerals* **2025**, *15*, 135. [[CrossRef](#)]
39. Djobo, J.N.Y.; Elimbi, A.; Tchakouté, H.K.; Kumar, S. Mechanical activation of volcanic ash for geopolymer synthesis: Effect on reaction kinetics, gel characteristics, physical and mechanical properties. *RSC Adv.* **2016**, *6*, 39106–39117. [[CrossRef](#)]
40. Fu, B.; Cheng, Z.; Wang, D.; Li, N. Investigation on the utilization of coal gasification slag in portland cement: Reaction kinetics and microstructure. *Constr. Build. Mater.* **2022**, *323*, 126587. [[CrossRef](#)]
41. Liu, Y.; Liu, Y.; Zhou, Y.; Lu, Y.; Cui, B.; Gao, H. Mechanical grinding time affected to performances of reject fly ash-based backfill binding material. *Coal Sci. Technol.* **2017**, *45*, 221–225. [[CrossRef](#)]
42. Xie, G.; Suo, Y.; Liu, L.; Zhu, M.; Xie, L.; Qu, H.; Sun, W. Mechanical grinding activation of modified magnesium slag and its use as backfilling cementitious material. *Case Stud. Constr. Mater.* **2023**, *18*, e01778. [[CrossRef](#)]

43. Yang, X.; Yang, J.; Wang, X.; Yin, S.; Yan, Z.; Zhang, X.; Li, G.; Chen, X.; Qi, Y.; Chen, W. Effects of curing age and magnesium slag grinding time on mechanical properties and hydration characteristics of magnesium slag-based backfill materials. *Case Stud. Constr. Mater.* **2025**, *23*, e05052. [\[CrossRef\]](#)
44. Yao, G.; Liu, Q.; Wang, J.; Wu, P.; Lyu, X. Effect of mechanical grinding on pozzolanic activity and hydration properties of siliceous gold ore tailings. *J. Clean. Prod.* **2019**, *217*, 12–21. [\[CrossRef\]](#)
45. Du, Y.; Wang, H.; Wang, Z.; Wang, Z.; Xia, H. Mineralogical and active mechanical excitation characteristics of filled fly ash cementitious materials. *J. Wuhan Univ. Technol.-Mater. Sci. Ed.* **2017**, *32*, 413–416. [\[CrossRef\]](#)
46. Ruan, S.; Liu, L.; Zhu, M.; Shao, C.; Xie, L.; Hou, D. Application of desulfurization gypsum as activator for modified magnesium slag-fly ash cemented paste backfill material. *Sci. Total Environ.* **2023**, *869*, 161631. [\[CrossRef\]](#) [\[PubMed\]](#)
47. Yang, P.; Liu, L.; Suo, Y.; Xie, G.; Sun, W.; Zhang, C. Physical-chemical coupling excitation of low activity coal gasification slag solid waste and its application as a backfill cementitious material. *Constr. Build. Mater.* **2023**, *401*, 132973. [\[CrossRef\]](#)
48. Zhao, Y.; Zhou, X.; Zhou, Q.; Cheng, F.; Guo, W. Solid waste binder cemented dihydrate phosphogypsum aggregate to prepare backfill material. *Miner. Eng.* **2025**, *226*, 109249. [\[CrossRef\]](#)
49. Hu, Y.; Hu, R.; Zhang, B.; Han, B. Research on mechanical properties and mix proportion design of solid waste-based cemented paste backfill. *Case Stud. Constr. Mater.* **2024**, *21*, e03618. [\[CrossRef\]](#)
50. Qi, W.; Ren, Q.; Zhao, Q.; Feng, Y.; Qi, W.; Han, Y.; Huang, Y. Effectiveness of soda residue-activated GGBS as alternative binder on compressive strength and workability of cemented paste backfills: Reuse of multi-source solid wastes. *Constr. Build. Mater.* **2022**, *348*, 128594. [\[CrossRef\]](#)
51. Liu, S.; Wang, Y.; Wu, A.; Shi, D.; Chang, Y.; Ruan, Z.; Li, Y. Electrolytic manganese residue-carbide slag-phosphorus slag ternary clinker-free backfill material: Synergistic mechanism and performance evolution. *Process Saf. Environ. Prot.* **2025**, *195*, 106839. [\[CrossRef\]](#)
52. Chen, W.; Chen, L.; Yin, S. Effect of bacteria-fly-ash based binder on cemented tailings backfill: Mechanical strength, solidified mechanism and economic benefits. *Constr. Build. Mater.* **2024**, *448*, 138292. [\[CrossRef\]](#)
53. Deng, X.; Yuan, Z.; Li, Y.; Liu, H.; Feng, J.; de Wit, B. Experimental study on the mechanical properties of microbial mixed backfill. *Constr. Build. Mater.* **2020**, *265*, 120643. [\[CrossRef\]](#)
54. Sun, W.; Wu, D.; Yilmaz, E.; Yang, G.; Liu, J. Delving into the role of microwave curing on the strength and cement hydration features of cemented tailings backfill. *Green Smart Min. Eng.* **2024**, *1*, 289–298. [\[CrossRef\]](#)
55. Zhu, D.; Huang, N.; Li, W.; Li, J.; Wu, X. Effect of different fibers and fiber contents on the mechanical properties and failure behavior of early age cemented lithium feldspar tailings backfill. *Dev. Built Environ.* **2024**, *19*, 100495. [\[CrossRef\]](#)
56. Jiang, J.; Wei, D.; Ou, X.; Chen, J.; Luo, Q. Effect of steel fibers on the thermal and mechanical properties of cementitious materials containing silicon carbide. *J. Build. Eng.* **2024**, *92*, 109779. [\[CrossRef\]](#)
57. Yaya, N.S.; Cao, S.; Yilmaz, E. Innovative reinforcement: Assessing strength features of waste microplastics reinforced backfills in sustainable mine waste management. *Constr. Build. Mater.* **2025**, *460*, 139744. [\[CrossRef\]](#)
58. Zhao, B.; Wen, J.; Zhai, D.; Tang, R.; Chen, S.; Xin, J. Effect of calcium chloride on the properties of gangue cemented paste backfill: Experimental results of setting time, rheological properties, mechanical strength and microscopic properties. *Case Stud. Constr. Mater.* **2025**, *22*, e04331. [\[CrossRef\]](#)
59. Sun, W.; Liu, L.; Zhou, J.; Zhao, Y.; Shao, C.; Lyu, Y. Effect of inorganic salt composition on strength, microstructure and leaching toxicity of coal-based solid waste backfill materials. *Process Saf. Environ. Prot.* **2024**, *192*, 1110–1126. [\[CrossRef\]](#)
60. Al-Moselley, Z.; Fall, M.; Haruna, S. Further insight into the strength development of cemented paste backfill materials containing polycarboxylate ether-based superplasticizer. *J. Build. Eng.* **2022**, *47*, 103859. [\[CrossRef\]](#)
61. Katsuyama, M.; Takemoto, M.; Sada, Y.; Yonezawa, Y.; Takeuchi, A.; Uesugi, M.; Okubo, T.; Wakihara, T. Insight into the crucial role of piperazine in CO₂ mineralization using calcium hydroxide and incineration fly ash. *Next Chem. Eng.* **2025**, *1*, 100013. [\[CrossRef\]](#)
62. Ratz, B.; Steindl, F.R.; Hassan, A.; Radinger, S.; Raič, S.; Sedlazeck, K.P.; Grengg, C. Evaluation of mineral waste streams for alkali-activated materials: Reactivity and utilization potential. *J. Build. Eng.* **2025**, *116*, 114705. [\[CrossRef\]](#)
63. Zhou, N.; Zhang, J.; Zhang, Y.; Yan, H. Carbon sequestration amount evolution characteristics and reaction mechanisms in coal-based solid waste backfill: A new whole-process carbon sequestration technique. *Int. J. Min. Sci. Technol.* **2025**, *S209526862500206X*. [\[CrossRef\]](#)
64. Yang, J.; Xiao, H.; He, X.; Su, Y.; Zeng, J.; Li, W.; Li, Y.; Qi, H. Rapid wet grinding carbonation of sintering red mud for highly efficient CO₂ sequestration and Cr solidification. *Chem. Eng. J.* **2024**, *488*, 151134. [\[CrossRef\]](#)
65. He, P.; Drissi, S.; Hu, X.; Liu, J.; Shi, C. Properties of CO₂-cured cement incorporating fly ash and slag subjected to further water curing. *Cem. Concr. Compos.* **2024**, *152*, 105633. [\[CrossRef\]](#)
66. Li, X.; Yin, S.; Wang, L.; Zhu, L.; Chen, W.; Zhuang, H. Synergistic and inhibitory mechanisms of CO₂ mineralization in fly ash-tailings backfill under different conditions. *J. CO₂ Util.* **2026**, *106*, 103389. [\[CrossRef\]](#)

67. Lu, X.; Xu, L.; Li, X.; Hou, Y.; Chen, Q.; Li, Q. In-situ mineral carbonation of ultramafic tailings for carbon dioxide removal: A critical review. *Process Saf. Environ. Prot.* **2025**, *204*, 108046. [\[CrossRef\]](#)
68. Ngo, I.; Ma, L.; Sajib, M.H.; Zhang, H.; Zhao, Z.; Yu, K.; Zhang, Z.; Peng, C. Examination of the use of binderless zeolite blend as backfill materials to enhance CO₂ adsorption in coal mine working face. *Case Stud. Constr. Mater.* **2024**, *21*, e03699. [\[CrossRef\]](#)
69. Klimkowska, K.M.; Uliasz-Bocheńczyk, A.S.G. A comprehensive review of CO₂ mineral sequestration methods using coal fly ash for carbon capture, utilisation, and storage (CCUS) technology. *Energies* **2024**, *17*, 5605. [\[CrossRef\]](#)
70. Li, Y.; Fu, J.; Jing, P.; Wang, J.; Wang, K. Experimental study on the macroscopic and microscopic properties of cement paste backfill after treatment with carbon dioxide carbonize filling slurries during the mixing process. *J. Mater. Res. Technol.* **2024**, *33*, 1654–1666. [\[CrossRef\]](#)
71. Gao, Y.; Liu, L.; Fang, Z.; He, W.; Zhang, B.; Zhu, M.; Yang, P.; Liu, Z.; Liu, D. A backfill material without cementitious material: Carbonation curing magnesium slag based full solid waste backfill material. *J. Cent. South. Univ.* **2024**, *31*, 1507–1525. [\[CrossRef\]](#)
72. Fang, Z.; Gao, Y.; He, W.; Zhu, M.; Xia, L.; Yang, P.; Liu, D.; He, J. Carbonation curing of magnesium-coal slag solid waste backfill material: Study on properties of flow, mechanics and carbon sequestration. *Case Stud. Constr. Mater.* **2024**, *20*, e03204. [\[CrossRef\]](#)
73. Guo, Y.; Zhang, J.; Long, K.; Ma, J.; Gao, Y.; Li, B. Experimental study on CO₂ sequestration capacity and mechanical characteristics evolution of solid wastes based carbon-negative backfill materials. *Constr. Build. Mater.* **2024**, *440*, 137457. [\[CrossRef\]](#)
74. Fang, Z.; Liu, L.; He, W.; Han, K.; Lan, H.; Gao, Y.; Sun, W.; Han, Z.; Xia, L.; Yang, P. Strength characteristics and carbonation depth evolution of modified magnesium slag based solid waste storage backfill materials. *J. Environ. Chem. Eng.* **2024**, *12*, 111975. [\[CrossRef\]](#)
75. Wang, P.; Mao, X.; Chen, S.-E. CO₂ sequestration characteristics in the cementitious material based on gangue backfilling mining method. *Int. J. Min. Sci. Technol.* **2019**, *29*, 721–729. [\[CrossRef\]](#)
76. Liu, L.; Xia, L.; Fang, Z.; Jia, Q.; Gao, Y.; He, W.; Liu, Z. Performance study of modified magnesium-coal based solid waste negative carbon backfill material: Strength characteristics and carbon fixation efficiency. *J. Environ. Chem. Eng.* **2024**, *12*, 113281. [\[CrossRef\]](#)
77. Chen, S.; Wang, C.; He, Z.; Liu, Y. CO₂ resource utilization in red mud modified phosphogypsum cementitious material: Strength development mechanism, heavy metals evaluation and carbon emission reduction effect. *Fuel* **2025**, *390*, 134684. [\[CrossRef\]](#)
78. Wang, B.; Cheng, H.; Liu, X.; Di, Z.; Song, H.; Zhang, D.; Cheng, F. CO₂ mineralized full solid waste cementitious material for coal mine goaf filling and carbon sequestration potential assessment. *Engineering* **2025**, *48*, 70–80. [\[CrossRef\]](#)
79. Wang, H.; Feng, G.; Qi, T.; Wang, L.; Ding, Q.; Pan, D.; He, J. Insight into the fracture mechanical properties of the interfacial transition zone of cemented coal gangue backfill under different stress angles by mesoscopic digital image correlation. *Eng. Fract. Mech.* **2024**, *300*, 109988. [\[CrossRef\]](#)
80. Peng, J.; Wu, Z.; Pan, Y.; Wang, J.; Wang, J.; Ren, S.; Xu, H. Enhancing the hydration properties of copper tailings cement through improving the interfacial transition zone by calcium-based activators. *Miner. Eng.* **2025**, *232*, 109542. [\[CrossRef\]](#)
81. Viradiya, J.; Gupta, R. The role of fiber surface treatment on improving mechanical performance of cementitious composites. *Constr. Build. Mater.* **2025**, *469*, 140452. [\[CrossRef\]](#)
82. Wang, H.; Feng, G.; Qi, T.; Gao, X.; Wang, C.; Wang, L.; Zhang, Z. Influence of the use of corn straw fibers to connect the interfacial transition zone with the mechanical properties of cemented coal gangue backfill. *Constr. Build. Mater.* **2023**, *367*, 130334. [\[CrossRef\]](#)
83. Zhang, C.; Guo, J.; Taheri, A.; Song, W.; Wang, X.; Xia, W. Mechanical characteristics and constitutive model of cemented tailings backfill under temperature-time effects. *J. Build. Eng.* **2024**, *96*, 110630. [\[CrossRef\]](#)
84. Liu, W.; Hu, Z.; Liu, C.; Huang, X.; Hou, J. Mechanical properties under triaxial compression of coal gangue-fly ash cemented backfill after cured at different temperatures. *Constr. Build. Mater.* **2024**, *411*, 134268. [\[CrossRef\]](#)
85. Liu, L.; Ding, X.; Tu, B.; Qu, H.; Xie, G. Energy evolution and mechanical properties of modified magnesium slag-based backfill materials at different curing temperatures. *Constr. Build. Mater.* **2024**, *411*, 134555. [\[CrossRef\]](#)
86. Libos, I.L.S.; Cui, L.; Liu, X. Effect of curing temperature on time-dependent shear behavior and properties of polypropylene fiber-reinforced cemented paste backfill. *Constr. Build. Mater.* **2021**, *311*, 125302. [\[CrossRef\]](#)
87. Xu, W.; Chen, W.; Tian, M.; Guo, L. Effect of temperature on time-dependent rheological and compressive strength of fresh cemented paste backfill containing flocculants. *Constr. Build. Mater.* **2021**, *267*, 121038. [\[CrossRef\]](#)
88. Xu, W.; Zhang, Y.; Chen, W. The investigation into the mechanical performance and microstructure evolution of cemented paste backfill disposal in surface storage suffering frost damage. *J. Environ. Manag.* **2025**, *377*, 124614. [\[CrossRef\]](#) [\[PubMed\]](#)
89. Ma, H.; Wang, Y.; Li, X.; Wang, J. Evolution law and mechanism analysis of strength for backfill under different stress and drainage conditions. *Constr. Build. Mater.* **2024**, *428*, 136406. [\[CrossRef\]](#)
90. Chen, S.; Yilmaz, E.; Wang, W.; Wang, Y. Curing stress effect on stability, microstructure, matric suction and electrical conductivity of cementitious tailings backfills. *Constr. Build. Mater.* **2022**, *360*, 129601. [\[CrossRef\]](#)
91. Ghirian, A.; Fall, M. Strength evolution and deformation behaviour of cemented paste backfill at early ages: Effect of curing stress filling strategy and drainage. *Int. J. Min. Sci. Technol.* **2016**, *26*, 809–817. [\[CrossRef\]](#)

92. Sun, W.; Sun, Q.; Shi, M. Durability and erosion mechanism of biomass-coal mixed combustion ash geopolymer backfill under compound erosion. *Constr. Build. Mater.* **2024**, *414*, 135023. [\[CrossRef\]](#)
93. Guo, Y.; Ran, H.; Feng, G.; Du, X.; Wei, T.; Wang, Z. Effects of curing under step-by-step load on mechanical and deformation properties of cemented gangue backfill column. *J. Cent. South. Univ.* **2020**, *27*, 3417–3435.
94. Zhao, Y.; Guo, Y.; Feng, G.; Li, C. Long-term strength and deformation size effect of gangue cemented backfill in acid mine water. *Structures* **2023**, *57*, 105114. [\[CrossRef\]](#)
95. Jiang, H.; Han, J.; Ren, L.; Guo, Z.; Yilmaz, E. Study of early-age performance of cementitious backfills with alkali activated slag under internal sulfate attack. *Constr. Build. Mater.* **2023**, *371*, 130786. [\[CrossRef\]](#)
96. Li, W.; Fall, M. Sulphate effect on the early age strength and self-desiccation of cemented paste backfill. *Constr. Build. Mater.* **2016**, *106*, 296–304. [\[CrossRef\]](#)
97. Zhu, G.; Zhu, W.; Fu, Y.; Yan, B.; Jiang, H. Effects of chloride salts on strength, hydration, and microstructure of cemented tailings backfill with one-part alkali-activated slag. *Constr. Build. Mater.* **2023**, *374*, 130965. [\[CrossRef\]](#)
98. Wu, F.; Fall, M. Sulphate-temperature-time interactions and their influence on rheological characteristics of cemented paste backfill. *Powder Technol.* **2024**, *440*, 119741. [\[CrossRef\]](#)
99. Al-Moselley, Z.; Fall, M. Understanding pore water pressure responses to sulphate in cemented tailings backfill with superplasticizers under thermo-hydro-mechanical-chemical field conditions. *J. Rock Mech. Geotech. Eng.* **2025**, *17*, 4673–4684. [\[CrossRef\]](#)
100. Hou, J.; Guo, Z.; Li, J.; Zhao, L. Study on triaxial creep test and theoretical model of cemented gangue-fly ash backfill under seepage-stress coupling. *Constr. Build. Mater.* **2021**, *273*, 121722. [\[CrossRef\]](#)
101. Cui, L.; Fall, M. A coupled thermo-hydro-mechanical-chemical model for underground cemented tailings backfill. *Tunn. Undergr. Space Technol.* **2015**, *50*, 396–414. [\[CrossRef\]](#)
102. Zhang, S.; Sun, W.; Hou, Z.; Wu, A.; Li, Z.; Wang, S.; Jiang, M.; Liu, Z. Research on damage and crack evolution mechanism of backfill under the coupling effect of layer-inclined angle-pore triple defect structure. *Constr. Build. Mater.* **2024**, *444*, 137793. [\[CrossRef\]](#)
103. Li, Z.; Sun, W.; Gao, T.; Zhao, J.; Lu, K.; Cheng, H. Experimental study on evolution of pore structure of inclined layered cemented tailings backfill based on X-ray CT. *Constr. Build. Mater.* **2023**, *366*, 130242. [\[CrossRef\]](#)
104. Jiao, H.; Zhang, Q.; Yang, Y.; Yang, T. Effect of interface roughness on mechanical properties of layered cemented tailings backfill. *Constr. Build. Mater.* **2023**, *409*, 134071. [\[CrossRef\]](#)
105. Zhang, S.; Sun, W.; Hou, Z.; Wu, A.; Wang, S. Study on the influence of contact surface characteristics on strength and fracture evolution of layered cemented backfill (LCB). *Case Stud. Constr. Mater.* **2024**, *20*, e03264. [\[CrossRef\]](#)
106. Wang, B.; Yang, L.; Li, Q.; Kang, M.; Liu, C.; Gan, S. Energy and deformation field evolution characteristics of layered cemented paste backfill under cyclic loading and unloading. *J. Build. Eng.* **2024**, *95*, 110103. [\[CrossRef\]](#)
107. Jiao, H.; Zhang, W.; Yang, Y.; Chen, X.; Yang, L.; Shen, H.; Rong, Y.; Zhang, H. Static mechanical characteristics and meso-damage evolution characteristics of layered backfill under the condition of inclined interface. *Constr. Build. Mater.* **2023**, *366*, 130113. [\[CrossRef\]](#)
108. Cao, S.; Song, W.; Yilmaz, E. Influence of structural factors on uniaxial compressive strength of cemented tailings backfill. *Constr. Build. Mater.* **2018**, *174*, 190–201. [\[CrossRef\]](#)
109. Wang, B.; Yang, L.; Li, Q.; Shu, X.; Kang, M. Mechanical behavior, acoustic emission and principal strain field evolution properties of layered cemented paste backfill under unconfined compression. *Constr. Build. Mater.* **2024**, *415*, 135111. [\[CrossRef\]](#)
110. Liu, C.; Wang, B.; Kang, M.; Li, Q.; Yang, L. Mechanical behavior and failure mode of cemented tailings backfill with prefabricated fractures: Effect of widths and angles. *Theor. Appl. Fract. Mech.* **2025**, *140*, 105121. [\[CrossRef\]](#)
111. Wang, Z.; Wang, Y.; Liu, Q.; Dino, G.A.; Ruan, Z.; Wu, A. Impact of weak interlayer characteristics on the mechanical behavior and failure modes of cemented tailings backfill: A study on thickness, strength, and dip angle. *Eng. Fail. Anal.* **2024**, *165*, 108795. [\[CrossRef\]](#)
112. Wang, J.; Song, W.; Cao, S.; Tan, Y. Mechanical properties and failure modes of stratified backfill under triaxial cyclic loading and unloading. *Int. J. Min. Sci. Technol.* **2019**, *29*, 809–814. [\[CrossRef\]](#)
113. Sun, W.; Zhang, S.; Li, J.; Li, Z. Experimental study on energy dissipation of layered backfill under impact load. *Constr. Build. Mater.* **2022**, *347*, 128478. [\[CrossRef\]](#)
114. Zhen, Y.; Du, X.; Feng, G.; Ju, F.; Li, X.; Wang, G. Uniaxial compression damage evolution of gangue-cemented backfill columns with different height-diameter ratios based on acoustic emission characteristics. *Chin. J. Eng.* **2024**, *46*, 1370–1380. [\[CrossRef\]](#)
115. Zhao, M.; Zhu, L.; Gu, W.; Liu, Z.; He, Z.; Ding, Z.; Qiu, H.; Li, Y. Mechanical properties and energy evolution law of variably-sized backfill bodies. *Coal Eng.* **2025**, *57*, 146–152.
116. Zhang, Y.; Xu, W.; Chen, W. The investigation into the mechanical properties and failure mechanisms of stratified cemented tailings backfill with enhancement layer under triaxial compression. *Eng. Fail. Anal.* **2025**, *182*, 110128. [\[CrossRef\]](#)
117. Zhao, Y.; Ran, H.; Feng, G.; Guo, Y.; Fan, Y. Damage evolution and failure characteristics of cemented gangue backfill body with different height-width ratios under uniaxial compression. *J. Min. Saf. Eng.* **2022**, *39*, 674–682. [\[CrossRef\]](#)

118. Guo, B.; Wu, P.; Liang, B.; Jin, J. The study on the damage evolution and size characteristics of gangue cemented backfill. *Case Stud. Constr. Mater.* **2025**, *22*, e04871. [[CrossRef](#)]
119. Hao, Y.; Li, Y.; Guan, J.; Xie, C.; Li, L.; Chen, S.; He, S.; Wei, S. Strength size effect model of fully substituted coal gangue concrete under coupled action of sulfate attack and dry-wet cycles. *Constr. Build. Mater.* **2025**, *467*, 140313. [[CrossRef](#)]

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