

Preparing Shotcrete Materials Applied to Roadways Using Gangue Solid Wastes: Influences of Mix Proportions of Materials on the Mechanical Properties

Meng Li, Shihao Xing, Yang Zhao *, Xiaobao Luo, Linlin Xie and Chunhui Xie

State Key Laboratory for Fine Exploration and Intelligent Development of Coal Resources, School of Mines, China University of Mining and Technology, Xuzhou 221116, China; cumtln@126.com (M.L.); ts22020059a31@cumt.edu.cn (S.X.); ts22020047a31@cumt.edu.cn (X.L.); ts23020203p31@cumt.edu.cn (L.X.); xiech@cumt.edu.cn (C.X.)

* Correspondence: starzykd@cumt.edu.cn; Tel.: +86-198-5162-8635

Abstract: Coal gangue is a waste product commonly produced during coal mining. Using gangue as a replacement for conventional aggregates in shotcrete applied to underground roadways is a feasible approach to promote the resource utilization of gangue solid waste. The mix proportions of shotcrete materials are crucial to the effectiveness of field applications. The aim of this study was to investigate the effects of mix proportions on the mechanical properties of the gangue-based shotcrete material applied to roadways. To achieve this, we conducted experiments to measure changes in the slump under different gangue sizes, mass concentrations, sand contents, and cement contents. The study analyzed the influences of various mix proportions on the conveying and mechanical properties of the gangue-based shotcrete material applied to roadways. The slump and the compressive strength were analysed. The following was concluded: (1) The gangue size and sand content have a similar effect on the slump. As the gangue size and sand content increase, the slurry slump initially decreases and then increases, which is attributed to the plasticity of the aggregates themselves. The mass concentration has a negative correlation with the slump, which is the least sensitive to changes in cement content. (2) The compressive strength of all specimens increases with prolonged curing, reaching its maximum after 28 d under the compressive experimental conditions. (3) This paper analyzed the reasons for better mechanical properties under the conditions of smaller size gangue, higher mass concentration, and higher cement content. It has also examined the reasons for greater compressive strength at 35% sand content. The experimental results of this paper also offer relevant guidance regarding the specific mix proportions of the material of the field gangue-based shotcrete material applied to roadways.

Keywords: roadways shotcrete materials; gangue; slump; mix proportions of materials; uniaxial compressive tests; mechanical properties



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1. Introduction

Gangue discharge is a common issue in coal mining and the separation of coal mines [1,2]. This process typically generates 15~20% solid waste, including gangue [3,4]. Currently, gangue is primarily disposed of by transporting and lifting it to the ground, where it is then stockpiled. The accumulation of gangue may give rise to a series of environmental issues, including the waste of land resources and the pollution of groundwater, and even trigger geological disasters such as landslides, debris flows, and fires. This restricts the sustainable development of coal mines [5–7]. Moreover, coarse aggregates, including gravels, are the primary raw materials used when preparing the shotcrete applied to coal mine roadways. The mining of these coarse aggregates has resulted in heightened ecological harm to both rivers and quarries [8]. The mining of industrial stone/aggregate is limited

by regulations. This has led to economic and social difficulties in the preparation of traditional shotcrete materials for roadways and coal mines [9]. Additionally, there is a general problem with the unstable performance of shotcrete materials on roadways, as illustrated in Figure 1. To solve these issues, some scholars have suggested using gangue solid waste to prepare shotcrete materials applied to roadways, replacing traditional shotcrete that uses gravel [10–12]. This approach allows for the direct underground resource utilization of gangue, and overcomes challenges related to gangue transportation and discharge [13]. However, gangue differs from traditional shotcrete materials, including gravel, in terms of the mechanical properties, so the mix proportions of gangue-based shotcrete materials applied to roadways prepared by replacing original aggregates with gangue exert different influences on the shotcrete materials. Considering this, studying the influence of various mix proportions of the gangue-based shotcrete material on its mechanical properties can help optimize the mix proportions and promote the material's resource utilization. This is significant to realizing the potential of gangue and promoting the material's application.

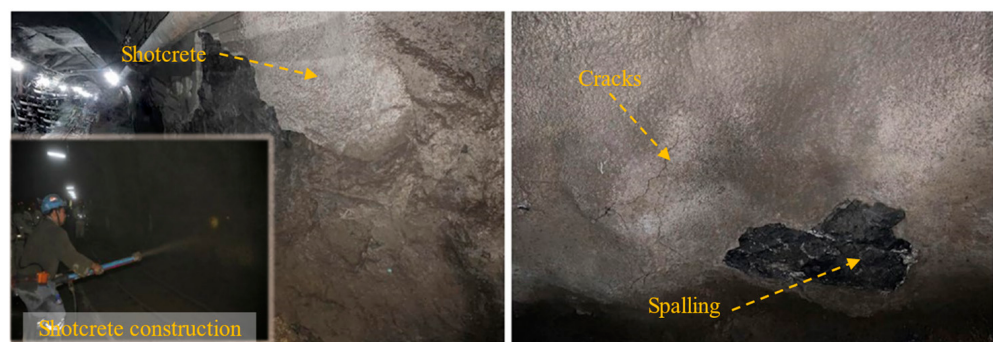


Figure 1. Roadway with shotcrete [14,15].

Scholars worldwide have studied the utilization of gangue by transforming it into shotcrete materials. Zhou et al. summarized the comprehensive disposal methods of gangue, including ground and underground disposal techniques. Using gangue to prepare building materials is an important method of consuming gangue [16]. J. Acordi et al. proposed using residual solid waste from mines to produce building materials as a method to promote the development of a recycling economy and realize innovation in clean energy. The application of gangue to concrete provides an important reference for the development of the shotcrete materials used in roadways [17]. In the experimental process, Benarchid Youssef et al. explored the crushing of concrete with gangue as aggregates in the compression process, and considered that the compressive strength and grain breakage are similar to those of concrete prepared with natural gravels and sand [18]. Xiao et al. provided the optimized mix proportions of non-activated gangue for preparing building concrete [19]. According to Liu et al. [20], the concrete columns made with gangue as coarse aggregates achieve sufficient adhesion to steel reinforcements. However, they do not prevent fracture propagation under high stress. Qiu et al. found that the addition of fly ash can enhance the working performance and mechanical properties of gangue-based concrete, as determined through nuclear magnetic resonance and grey correlation analysis [21]. Chen et al. conducted experimental studies on the effects of aggregate (gangue) content and water/cement ratio on shotcrete, and discussed their positive impact on CO₂ emission reduction in the field of environmental protection [22]. Zhang et al. used a cement-based paste to coat the surface of gangue aggregates, in order to enhance the mechanical and interfacial properties, and they verified that the CO₂ emissions associated with such concrete are only 73.3% of those arising from the use of conventional concrete of the same label [23]. In other aspects, Huang et al. conducted numerical research into the macroscopic mechanical behaviors and microscopic particle motions of gangue with different sizes under different confining pressures and at different loading rates [24]. Li et al. adopted particle flow code (PFC) to simulate the influences of different gangue sizes on the compressive deformation of gangue particles [25]. Additionally, gangue, as an industrial waste, is also mainly used for backfill-

ing in mines, power generation, road paving, and brickmaking. For instance, Zhang et al. summarized the technical framework of coal mining with direct gangue backfilling and gangue grouting as well as filling, and improved the technological system of comprehensive gangue disposal and utilization [26]. A. Arulrajah et al. conducted triaxial compression tests to verify the feasibility of using gangue to pave road subgrades [27]. Other studies have investigated the effect of a gangue aggregate on basic physical properties, such as the modulus of elasticity and pore structure, of concrete [28,29]. Currently, the proportions of other ingredients in gangue aggregate concrete and the environmental impacts are still being refined [30–32]. The aforementioned research indicates that the application of gangue as a concrete aggregate offers broad potential for both future research and applications. Existing research mainly focuses on the comparison of building concrete prepared with gangue as the aggregate with traditional concrete, in addition to the influences of gangue sizes on the compressive deformation of gangue [33–36]. The mechanical properties of gangue-based shotcrete materials with different mix proportions have yet to be systematically explored. The influences of overall mix proportions on the mechanical properties of shotcrete materials applied to mine roadways are seldom studied.

The objective of this study was to investigate the effects of mix proportions on the mechanical properties of gangue-based shotcrete material used in roadways. Single-factor rotational experiments were conducted to examine the impacts of gangue size, mass concentration, sand content, and cement content on the slump of the material. Then, the influences of different mix proportions on the mechanical properties of the material were determined by analyzing the compressive strengths of specimens. This is expected to optimize the application of roadway support materials, promote and expand the resource utilization of solid wastes, including gangue, and improve the sustainable development of the mining industry. To achieve this, crushed gangue was used to prepare the shotcrete materials applied to roadways instead of traditional stone. Additionally, the research focusing on the use of gangue material in the preparation of ordinary building concrete has been extended. This is expected to promote and expand the resource utilization of solid wastes, and improve the sustainable development of the mining industry. The influence of the mix proportions of materials on the conveying and mechanical properties was studied to optimize the application of roadway support materials. This has significant implications for the specific mix proportions of the material used in the field of gangue-based shotcrete applied to roadways.

2. Specimen Preparation and Experimental Schemes

The gangue-based shotcrete material applied to roadways was here prepared from gangue, cement, sand, and water as the basic materials. With reference to the GB/T 35159-2017 Flash setting admixtures for shotcrete [37], a small amount of a rapid-setting admixture was added. The single-factor rotation experiments were designed with gangue particle size, mass concentration, sand content, and cement content as transforming factors to test the slump and mechanical properties of the specimen after slurry collapse.

2.1. Experimental Materials and Specimen Preparation

The raw materials used to prepare the specimens included gangue, cement, sand, and water. The gangue used in the experiments was all separated gangue from the Hegang Coal Mine (Jining City, Shandong Province, China, as shown in Figure 2), with sizes of 0~50 mm. The gangue here was typical of sandstone, with medium hardness, and belonged to the harder type of gangue. When tested, the natural moisture content was determined to be less than 1% and the water absorption rate was 4.49%. A crusher and a sieving machine were used to obtain gangue with sizes of 0~2.5, 2.5~5, 5~10, and 10~15 mm. The cement used was PO_{42.5} standard Portland cement; its main components were 2CaO·SiO₂, 3CaO·SiO₂, 3CaO·Al₂O₃, etc., and common river sand was used.

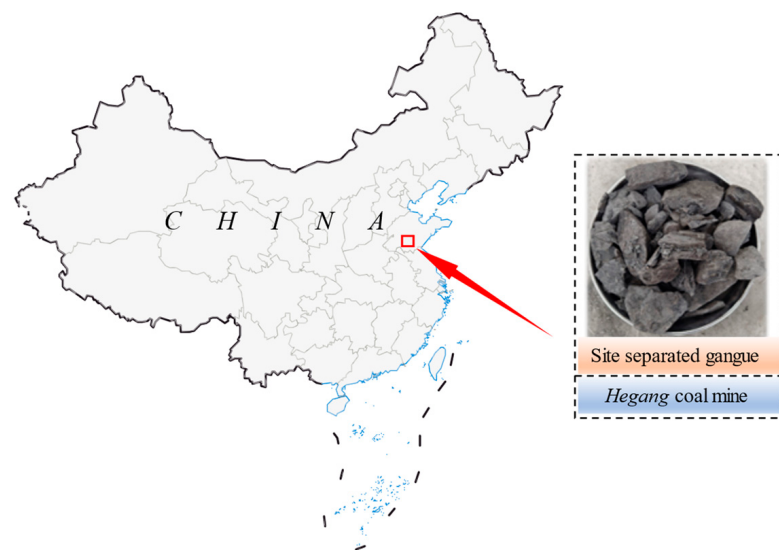


Figure 2. Sampling location and appearance of gangue.

When calculating the amount of shotcrete material applied to roadways, the bulk density of gangue mass, a non-continuous medium, is a crucial factor. This refers to the density of each particle size range in the stacking state. To obtain the bulk density of gangue, the volume of gangue with a specific mass and the same particle size was tested using a steel barrel. Figure 3 shows the bulk state of different gangue sizes, and Table 1 presents the measured bulk densities of gangue with different particle sizes.

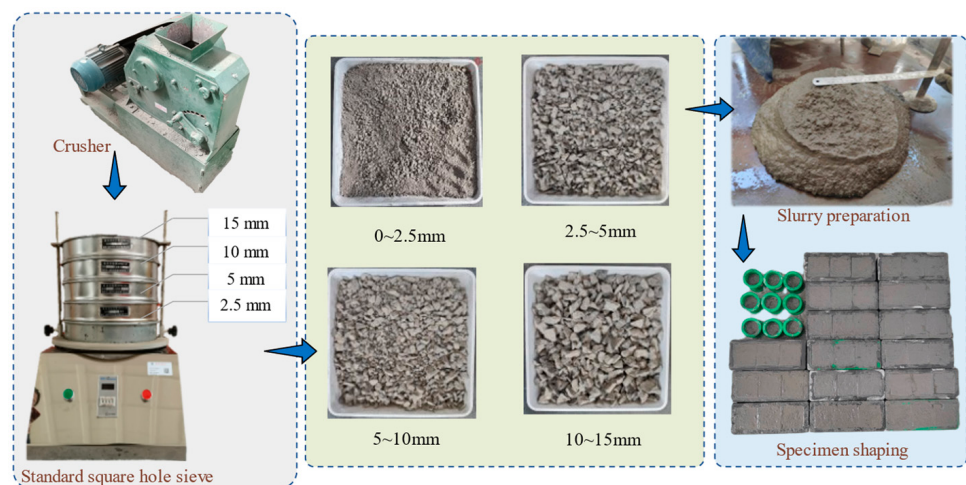


Figure 3. Specimen preparation.

Table 1. Mass density and bulk density of gangue.

Mass Density/kg·m ⁻³		Bulk Density/kg·m ⁻³			
2675	Particle size range	0~2.5 mm	2.5~5 mm	5~10 mm	10~15 mm
		1596	1368	1241	1263

X-ray component testing and a microscopic analysis of gangue specimens were performed, as shown in Figures 4 and 5.

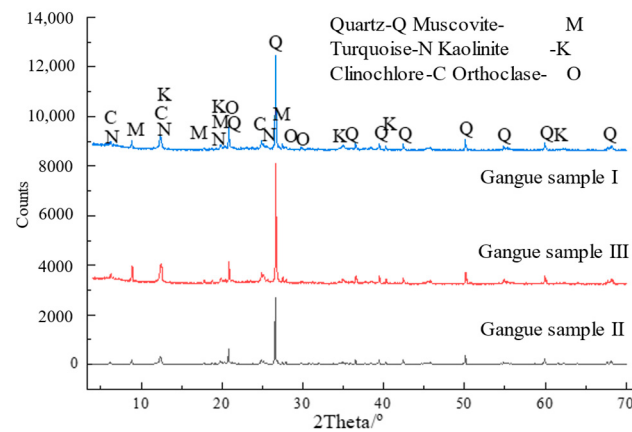


Figure 4. Mineral composition of gangue.

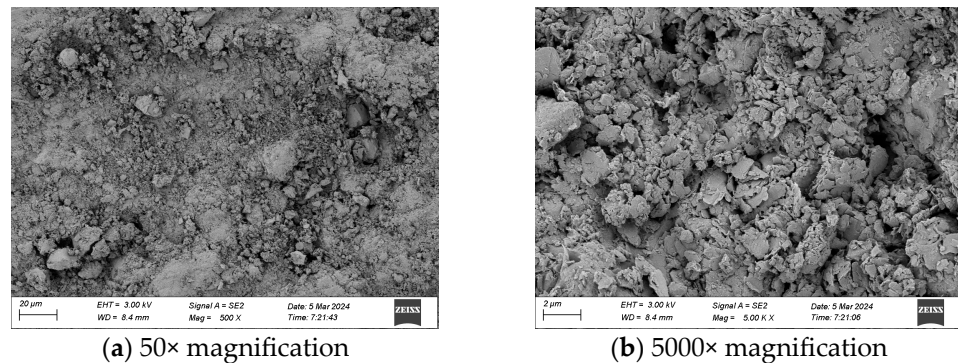


Figure 5. Gangue microstructure.

The minerals in this material are mainly quartz, kaolin and normal feldspar. Quartz is a stable mineral that can enhance the material's strength and improve the bearing capacity between particles. The surface of the gangue material is uneven, with some tiny pores and cracks, but they do not form a complete network of cracks. The material as a whole is compact and has good integrity. The edges of the pores and cracks, as well as the surrounding particles, are well cemented.

The particle size of a fine aggregate (sand) must not exceed 4.75 mm, the void rate must be less than 44%, and the loose bulk density must be less than 1400 kg/m³.

The specimen formation process included two processes: slurry preparation and curing. The specimen preparation process is shown in Figure 3.

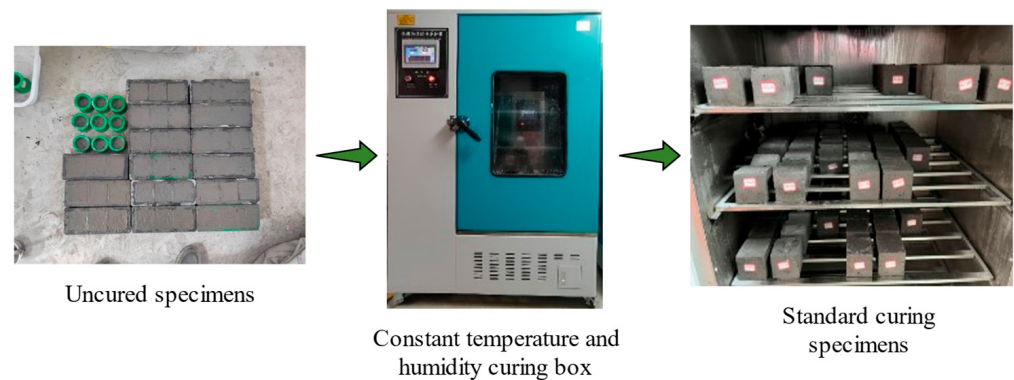
Slurry preparation: Based on pre-test results and the results of a survey on an underground mine site, the gangue size ranged 0~15 mm with a mass concentration of 69~78%, sand content of 15~45%, and cement content of 9~18%, as shown in Table 2. A total of 16 groups of the gangue-based shotcrete materials applied to roadways (A₁~A₄, B₁~B₄, C₁~C₄, and D₁~D₄) were prepared using single-factor rotational experiments. The percentages in the table represent the mass percentages of raw materials.

During the preparation process, the pre-weighed coarse aggregate, fine aggregate, and cement were first mixed and stirred for 5 min. After that, the evenly mixed accelerator as well as water were injected into the dry material and stirred for another 5 min at a speed of 15 turns per minute. This process should be carried out in accordance with the conditions in the laboratory and the technical specification for application of sprayed concrete [38]. The total mass of solid materials in each group of experiments, including gangue, sand, and cement, was set at 8 kg. The specific water consumption was calculated based on the mass concentration, as shown in Table 2. The density of the gangue-based shotcrete slurry prepared according to the schemes ranged from 2300 kg/m³ to 2490 kg/m³, with an average density of 2385 kg/m³.

Table 2. Mix proportions of raw materials of the gangue-based shotcrete material used in single-factor rotational experiments.

No.	Gangue Size/mm	Mass Concentration/%	Sand Content/%	Cement Content/%	Water Consumption/kg
A ₁	0~2.5	75	25	12	2.67
A ₂	2.5~5				
A ₃	5~10				
A ₄	10~15				
B ₁	2.5~5	69	25	12	3.59
B ₂		72			3.11
B ₃		75			2.67
B ₄		78			2.26
C ₁	2.5~5	75	15	12	2.67
C ₂			25		
C ₃			35		
C ₄			45		
D ₁	2.5~5	75	25	9	2.67
D ₂				12	
D ₃				15	
D ₄				18	

Specimen curing: The gangue-based shotcrete material applied to roadways in schemes A₁ to D₄ was poured into plastic cube molds measuring 70.7 mm × 70.7 mm × 70.7 mm. The specimens were then cured in a wet curing box at a temperature of 23 ± 2 °C and a relative humidity above 95%, as shown in Figure 6. The curing periods were set to 1, 3, 7, 14, and 28 d.

**Figure 6.** Specimen curing and mechanical tests.

2.2. Experimental Schemes

2.2.1. Slump Tests

Studying the slump of specimens is of significance when assessing properties [36]. Under the guidance of the Technical Specification for Application of Sprayed Concrete and Standard for Quality Control of Concrete [38,39], the slump of the 16 groups (A₁~D₄) was measured.

The gangue-based shotcrete slurry was poured twice into a slump cylinder placed at the center of a wet plate on a horizontal table. The glass plate and inner wall of the slump cylinder were uniformly wetted prior to the test. A wet cloth was placed over the slump cylinder for later use. A ramming bar was used to tamp the slurry 15 times. After flattening the surface with a scraper, the cylinder was slowly lifted vertically. After 10 s, a steel ruler was used to measure the maximum diameters along two directions perpendicular to each other. The mean value of these measurements was taken as the slump of this type of gangue-based shotcrete material (Figure 7).

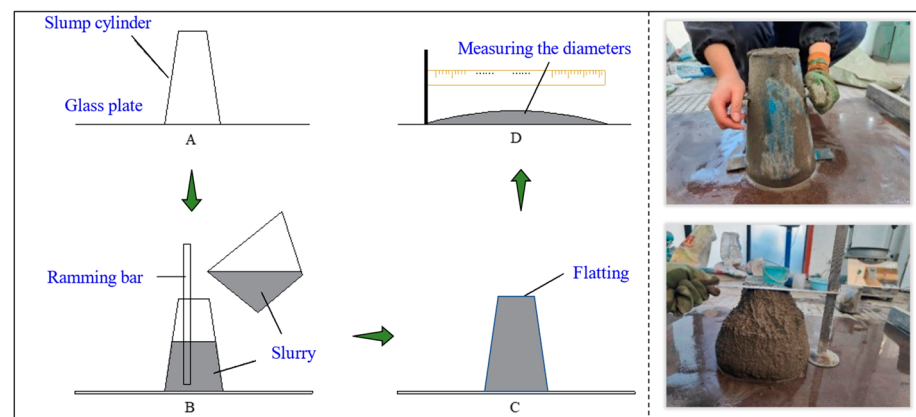


Figure 7. Slump testing.

2.2.2. Compressive Strength Tests

A WAW-1000D electro-hydraulic (Manufactured by SENS, Shenzhen, China) servo universal testing machine was used to carry out uniaxial compressive tests on specimens cured for 1 d, 3 d, 7 d, 14 d, and 28 d in each group. The loading rate was 0.5 mm/min until reaching the target axial displacement of 20 mm. The process of testing the mechanics of the gangue-based shotcrete material applied to roadways draws on the basic mechanical testing process of rock.

3. Experimental Results and Discussion

Conveying and mechanical properties are crucial to the practical use of roadway shotcrete materials. This chapter analyzes the test results of slurry slump and the compressive strength of the gangue-based shotcrete material to study its applicability and potential applications. The effects of the mix proportions of materials on the conveying and mechanical properties of the gangue-based shotcrete material were obtained.

3.1. Influences of Mix Proportions on Slump of the Gangue-Based Shotcrete Material

According to the Technical Specification for Application of Sprayed Concrete and Standard for Quality Control of Concrete [38,39], the optimum range of shotcrete slump is 80–220 mm under the condition of ensuring the concrete's compatibility and pumping ability. The slump of the gangue-based shotcrete material was recorded in each of the 16 single-factor rotational experiments. The sensitivity of the slump to changes in each proportioning factor is plotted in Figure 8.

- (1) When changing only the gangue size, the slurry slump tends to decrease initially and then increase as the gangue size enlarges. In the experimental range of 0–10 mm, the slump decreased from 265 mm to 201 mm as the gangue size increased. However, it increased again to 245 mm when the gangue size was in the range of 10–15 mm. The increase in the gangue size enhanced the plasticity of aggregates in the slurry. Fine aggregates, including cement, can fill in the gaps between gangue and sand particles, causing the slump to gradually decrease. However, if the gangue size increases further, gaps in the slurry gradually widen, and the slurry cannot accumulate. This results in limited adhesion between particles, poor flow plasticity, and increased slump.
- (2) The slump is negatively correlated with the mass concentration, meaning that as the mass concentration increases, the slump decreases. The slump ranges from 272 to 267 mm when the mass concentration is in the range of 69–72%. If the mass concentration increases beyond this range, the slump reduces significantly, reaching 224 to 201 mm when the mass concentration is 75–78%. A high-concentration slurry results in poorer fluidity in the gangue-based shotcrete material when applied to roadways, which can cause it to set and accumulate into blocks, leading to a decrease in slump.

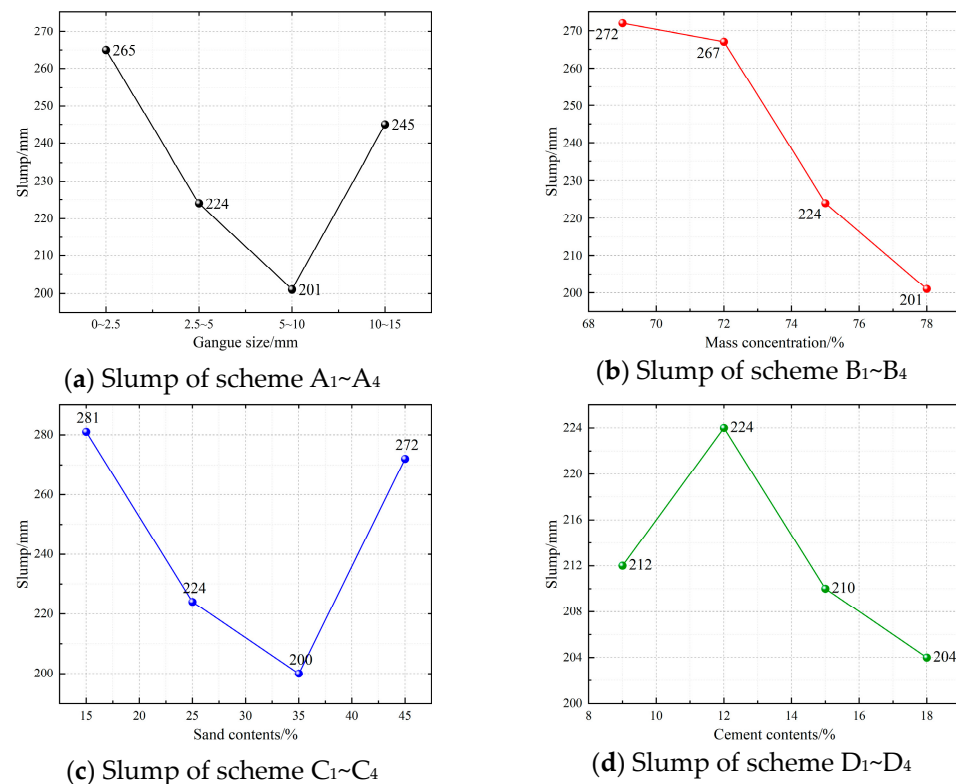


Figure 8. Influences of mix proportions on the slump.

- (3) After altering the sand content, the slump initially decreases, and it then increases as the sand content increases. This trend is similar to the effect of the gangue size. At a sand content of 35%, the slump reaches its minimum at 200 mm. This is because as the sand content increases, the plasticity of the slurry gradually increases while the slump decreases. If the sand content increases further, the plasticity of the slurry deteriorates due to the low bonding capacity of sand. As a result, the shotcrete slurry cannot remain intact and the slump gradually increases.
- (4) Cement is an inorganic cementing material used to bond other raw materials. Increasing the cement content in the gangue-based shotcrete material applied to roadways within the range of 9% to 12% results in an increase in slump from 212 to 224 mm. However, further increasing the cement concentration to 18% leads to a decline in slump to 204 mm. The increment of cement content increases the amount of cementing materials as well as the cohesiveness, which results in a reduction in slump. Overall, the effects of cement concentration on the slump are less significant than other material proportioning factors. This is due to the fact that cement does not contribute to hardening in the initial stage of curing. However, increasing the cement content appropriately can improve the flow plasticity of the specimens.

3.2. Influences of Mix Proportions on Mechanical Properties of the Gangue-Based Shotcrete Material Applied to Roadways

The Technical Code for Engineering of Ground Anchorages and Shotcrete Support [40] provides a range of average compressive strength values for wet shotcrete at 1 d and 28 d. On this basis, the results of the experiment have been analyzed.

During the early curing period, there were only minor differences in the compressive strengths of the specimens. However, after being cured for 28 d, the compressive strength reached its maximum value, and the difference became significant. This suggests that altering the mix proportions of materials in the gangue-based shotcrete material applied to roadways has a significant impact on its mechanical properties. Through experimental research, some scholars have determined the compressive strength of gangue-based con-

crete, which can reach tens of MPa. This was achieved by adding a variety of rapid-setting admixtures. Other scholars have carried out the activation modification of gangue. Compared to the strength of concrete studied by previous researchers, the compressive strength of the gangue-based shotcrete material applied to roadways in this experiment is lower than that ordinary concrete, but the difference is within 30%. Its mechanical properties are weakened by the lower strength of the gangue material.

3.2.1. Influence of the Gangue Size

Table 3 lists the peak compressive strengths of the gangue-based shotcrete specimens prepared following schemes A₁~A₄ with curing periods of 1 d, 3 d, 7 d, 14 d, and 28 d. On this basis, changes in the curves of the specimens under schemes A₁~A₄ with different curing periods are plotted in Figure 9.

Table 3. Peak compressive strengths of the gangue-based shotcrete specimens prepared under schemes A₁~A₄ with different curing periods.

Peak Compressive Strength/MPa	1 d	3 d	7 d	14 d	28 d
A ₁	0.52	0.68	1.4	2.32	3.47
A ₂	0.76	1.02	1.79	2.5	3.54
A ₃	0.7	0.89	1.71	2.06	2.79
A ₄	0.62	0.82	1.56	1.91	2.48

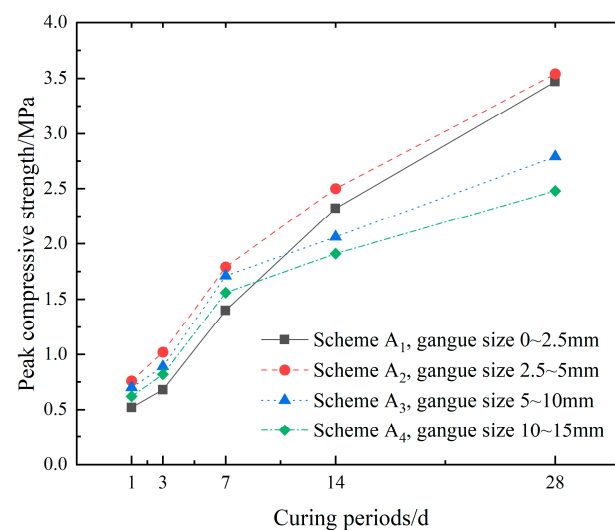


Figure 9. Influence of the gangue size on the compressive strength of the gangue-based shotcrete material applied to roadways.

Table 3 and Figure 9 demonstrate that the compressive strength increases with the lengthening of the curing period for specimens of all gangue sizes. This is due to the gradual reduction in water content in the specimens and the more complete cementation of the aggregates. Among the specimens subjected to the same curing period, those under scheme A₂ (gangue size: 2.5~5 mm) exhibit significantly higher compressive strength than those under schemes. After 28 d of curing, the compressive strength of specimens in scheme A₂ reached 3.54 MPa. This is, respectively, 1.02, 1.27, and 1.43 times higher than the compressive strengths of specimens under schemes A₁, A₃, and A₄.

Increasing the size of the gangue can improve the strength of the specimens in three ways: by compacting the aggregate arrangement, enhancing the aggregate skeleton effect, and increasing the coverage of water cement hydration products.

A reasonable particle size can improve the uniform arrangement of gangue in concrete voids and enhance the compactness of concrete specimens. When compared to gangue with

larger particle sizes (schemes A₃ and A₄), the filling capacity of gangue-based shotcrete material is insufficient, resulting in poor concrete compactness. Simultaneously, homogenizing the material specimens will stabilize their aggregate skeleton structure. This is the reason why the overall compressive strength of small-particle-size gangue-based shotcrete material specimens is significantly higher. Reducing the gangue particle size increases its surface area, allowing water cement hydration products to cover the surface more easily.

The curing period of 14 d was taken as a boundary. The results show that specimens under scheme A₁ have lower compressive strengths than those under schemes A₃ and A₄ when the curing period is shorter than 14 d. Conversely, when the period is prolonged, the compressive strengths of specimens under scheme A₁ exceed those of specimens under schemes A₃ and A₄. Finally, specimens under scheme A₁ exhibit compressive strengths similar to those of specimens under scheme A₂, reaching 3.47 MPa. This phenomenon occurs because, during the early curing period, the compressive strength of specimens is mainly attributed to the compressive capacity of the aggregates themselves. Therefore, specimens' compressive capacity increases with larger gangue size during a short curing period. Conversely, shotcrete materials prepared with smaller gangue sizes have more uniformly distributed internal components, resulting in a better bearing capacity after a long curing period.

3.2.2. Influence of the Mass Concentration

Table 4 displays the peak compressive strengths of gangue-based shotcrete specimens under schemes B₁~B₄ with curing periods of 1 d, 3 d, 7 d, 14 d, and 28 d. Based on these data, Figure 10 shows the change curves of the peak compressive strengths of the specimens under schemes B₁~B₄ with different curing periods.

Table 4. Peak compressive strengths of gangue-based shotcrete specimens under schemes B₁~B₄ with different curing periods.

Peak Compressive Strength/MPa	1 d	3 d	7 d	14 d	28 d
B ₁	0.31	0.64	1.15	1.48	1.81
B ₂	0.45	0.75	1.35	1.97	2.23
B ₃	0.51	1.11	1.69	2.26	3.34
B ₄	0.64	1.52	2.42	2.85	3.61

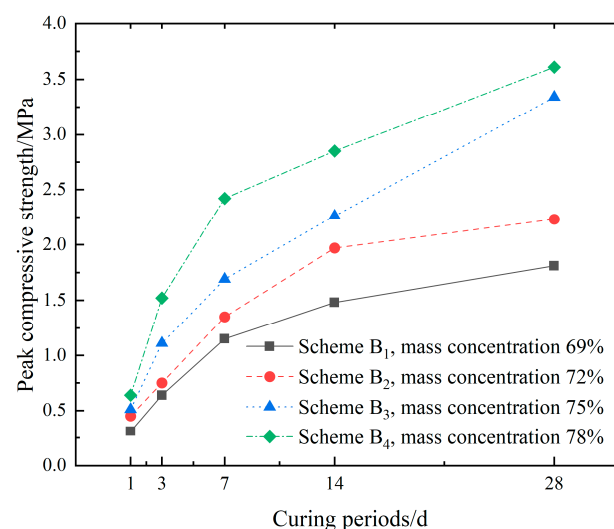


Figure 10. Influence of different mass concentrations on the compressive strength of the gangue-based shotcrete material applied to roadways.

Table 4 and Figure 10 demonstrate that the cement hydration reaction continues, and cementing material fills the capillary pores, as the curing period is prolonged [40]. As a result, the compressive strengths of all mass concentration specimens increase. Additionally, an increase in mass concentration leads to an increase in compressive strength after the same curing period. Figure 10 lists various schemes in descending order after all curing periods. According to the peak compressive strengths of corresponding specimens, the compressive strengths of specimens under scheme B₄ reach the maximum (3.61 MPa) when the curing period is 28 days. The other schemes, B₃, B₂, and B₁, have lower compressive strengths.

The increase in mass concentration is equivalent to a reduction in the water/cement ratio of the specimens during the initial period. The decrease in water content during the setting and curing processes reduces the number of pores and fractures in the specimens, thereby improving their compressive strength.

An increase in the water/cement ratio results in a decrease in the dispersion performance of cement hydration products, making it difficult for them to form a strong skeleton structure. Analyzing the material's conveying properties, an increase in water/cement ratio (resulting in a reduced mass concentration) leads to the increased fluidity of the shotcrete slurry, which makes the aggregate of the shotcrete slurry easier to deposit, resulting in an uneven distribution of the aggregate and reduced mechanical properties in gangue-based shotcrete material specimens.

Furthermore, it was observed that shotcrete specimens with different mass concentrations achieve comparable compressive strengths in a short curing period. However, as the curing period is prolonged, specimens with a higher mass concentration gradually demonstrate their superiority in terms of compressive strength. Figure 10 illustrates that, after 28 d curing, the compressive strengths of specimens under schemes B₄ and B₃ are higher than those subjected to schemes B₁ and B₂.

3.2.3. Influence of the Sand Content

Table 5 presents the peak compressive strengths of gangue-based shotcrete specimens under schemes C₁~C₄ with curing periods of 1 d, 3 d, 7 d, 14 d, and 28 d. According to these data, changes in the peak compressive strength of specimens under schemes C₁~C₄ after various curing periods were plotted, as displayed in Figure 11.

Table 5. Peak compressive strengths of gangue-based shotcrete specimens under schemes C₁~C₄ with different curing periods.

Peak Compressive Strength/MPa	1 d	3 d	7 d	14 d	28 d
C ₁	0.34	0.63	0.95	1.48	1.98
C ₂	0.49	0.89	1.69	2.5	3.45
C ₃	0.56	1.11	2.24	3.56	3.89
C ₄	0.47	0.66	1.31	2.11	2.61

Table 5 and Figure 11 demonstrate that the compressive strengths of specimens under schemes C₁~C₄ also increase with prolonged curing, which is consistent with changes under schemes A₁~A₄ and B₁~B₄. Additionally, when the curing period remains fixed, the compressive strengths of specimens gradually increase with sand content under schemes C₁~C₃. However, if the sand content is increased further, as per scheme C₄, the compressive strength decreases significantly.

Specimens cured under scheme C₃ exhibit the highest compressive strength across all curing periods. For instance, when the curing period is 28 d, the peak compressive strength of specimens under scheme C₃ is 3.89 MPa. This is 1.96, 1.13, and 1.49 times higher than those under schemes C₁, C₂, and C₄, respectively. The fine aggregate, sand, contributes to the bearing capacity of the shotcrete material. Therefore, as increase in sand content results in an increase in the compressive strength of specimens. However, excessive sand use results in loose specimens during the initial stage, leading to a decrease in strength.

Additionally, a forms voids in the specimens, causing the cracking and deformation of the specimens, which further reduces their strength.

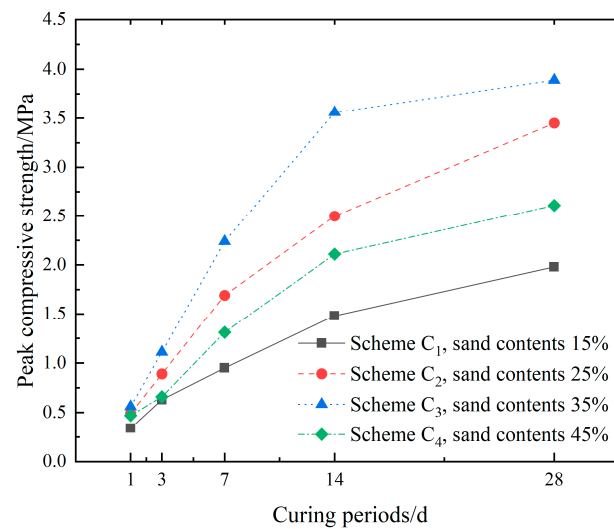


Figure 11. Influences of different sand contents on the compressive strength of the gangue-based shotcrete material applied to roadways.

In addition, sand alone lacks the ability to form cement, requiring external cementing substances to ensure the strength and ease of use of the shotcrete. The amount of cementing substances required increases with higher sand content. The sand content and cement dosage are closely linked, similarly to the effect of gangue size on the strength of the specimens. When selecting sand size for on-site shotcrete, it is important to note that the sand size is negatively correlated with the cement dosage within the limits of the regulations.

3.2.4. Influences of the Cement Content

Table 6 displays the peak compressive strengths of the gangue-based shotcrete specimens under schemes D₁~D₄ with curing periods of 1 d, 3 d, 7 d, 14 d, and 28 d. Figure 12 shows the changes in the peak compressive strengths of specimens under schemes D₁~D₄ with various curing periods.

Table 6. Peak compressive strengths of the gangue-based shotcrete specimens under schemes D₁~D₄ with different curing periods.

Peak Compressive Strength/MPa	1 d	3 d	7 d	14 d	28 d
D ₁	0	0.26	0.89	1.62	2.32
D ₂	0.31	0.56	1.49	2.26	3.03
D ₃	0.35	0.67	1.71	2.57	3.35
D ₄	0.46	1.16	2.48	2.89	3.52

Table 6 and Figure 12 show that the compressive strengths of specimens under schemes D₁~D₄ improve with prolonged curing, consistent with the effects of other mix-related factors on the mechanical properties of such specimens.

Specimens cannot be formed under scheme D₁ after being cured for 1 d, resulting in a compressive strength of 0. However, under schemes D₁~D₄, the compressive strength gradually increases with an increase in cement content after the same curing period. After curing for 28 d, the peak compressive strengths of specimens prepared under schemes D₁~D₄ are 2.32, 3.03, 3.35, and 3.52 MPa, respectively. Increasing the cement content results in a decrease in specimen porosity, an increase in density, and an increase in the area bound to the aggregate, as well as an increase in compressive strength.

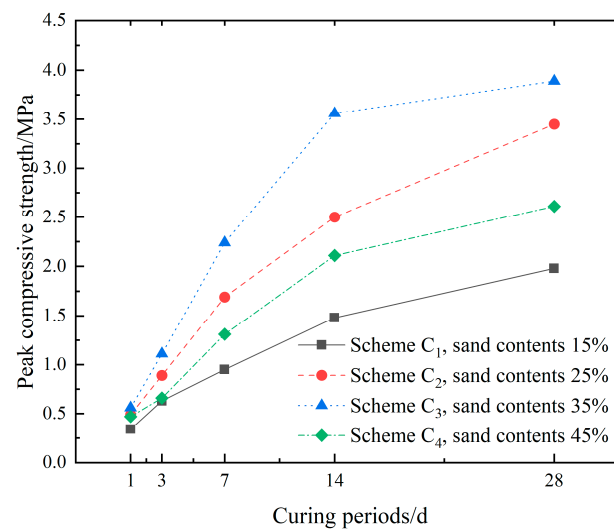


Figure 12. Influences of different cement contents on the compressive strength of the gangue-based shotcrete material applied to roadways.

On the other hand, on-site experience indicates that cement content cannot be increased indefinitely. Excessive cement content leads to poorer plasticity and increases the likelihood of cracking during the later stages of curing. Correspondingly, the cost also increases. Excessive cement results in an uneven distribution of cement paste within concrete specimens, making it difficult to form a uniform and stable structure. This leads to the presence of voids and a decrease in the material's forming ability, ultimately affecting the mechanical properties of the specimens. Additionally, the hydration reaction of cement releases more heat. The formation of contractions and cracks within concrete specimens is exacerbated by the combined effects of hydration products and accumulated heat, particularly during the early stages of the curing period [41]. This phenomenon did not occur in this case, as the cement content did not exceed a reasonable value under schemes D₁~D₄.

Additionally, the early strengths of specimens prepared under schemes D₁~D₄ grow much faster than the later strengths, as do the compressive strengths of specimens under schemes A₁~A₄, B₁~B₄, and C₁~C₄. This can be attributed to the fact that the presence of C₃A and C₃S in cement enhances the early-age strengths, while the late-age strengths exhibit a slower increase. Secondly, with the development of the cement-grinding process, cement clinkers can be ground to greater fineness. Fine particles, smaller than 1 µm in diameter, accelerate the rate of the cement's hydration, improving the early-age strength while contributing little to late-age strength.

4. Conclusions

To address the economic cost and social issues associated with traditional shotcrete materials applied to roadways, this study utilized typical gangue as the raw material. The laboratory experimental method was employed to design single-factor rotational experimental schemes and processes. Based on these findings, the study explored the effects of the mix proportions of materials on the slump and the mechanical properties of the gangue-based shotcrete material applied to roadways. These properties have a significant impact on the conveying properties and mechanical properties of the gangue-based shotcrete slurry applied to roadways. The study drew the following conclusions:

- (1) The gangue size and sand content have an impact on the slump of the gangue-based shotcrete slurry applied to roadways. Increasing the size of the gangue and sand content leads to a decrease in slump, followed by an increase due to the plasticity of the aggregate. The slump is negatively correlated with the mass concentration and is least affected by changes in the cement content;

- (2) The compressive strengths of the specimens prepared under schemes A₁~D₄ all increase with prolonged curing. In a curing period of 28 d, the compressive strengths of the specimens all reach a maximum under the corresponding experimental conditions;
- (3) When the curing period is 28 d, specimens under scheme A₂ (gangue size: 2.5~5 mm) exhibit the highest compressive strength. This is due to the fact that smaller gangue is stressed more uniformly and has a larger bound area cementing the aggregates. Additionally, increasing the mass concentration reduces the water/cement ratio of specimens, which in turn decreases the number of pores and fractures in the specimens. As a result, specimens under scheme B₄ (mass concentration: 78%) also exhibit high compressive strength. Sand has a certain mechanical bearing capacity. However, excessive sand results in voids in the specimens. Therefore, specimens prepared under scheme C₃ (with 35% sand content) have the highest compressive strength. As the cement content increases, the porosity of the specimens decreases, the density increases, and the bound area increases. Therefore, specimens prepared under scheme D₄ (with 18% cement content) exhibit the largest compressive strength.

The conveying and mechanical properties of the gangue-based shotcrete material applied to roadways vary significantly depending on the mix proportions of materials in the experiment. In practical engineering applications, the ability of shotcrete material is determined by various factors, such as gangue lithologies, geological conditions, and strength. Therefore, the results of this experiment are also significant in guiding the specific mix proportions of materials used in field gangue-based shotcrete applied on roadways. Furthermore, the addition of a rapid-setting admixture and other chemicals during the preparation of the gangue-based shotcrete material applied to roadways will also be studied in subsequent research.

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