ISSN: 2472-3703 DOI: 10.6911/WSRJ.202609_12(9).0014

Study on Mix-Proportion Optimization and Performance Test of Low-Rebound Shotcrete for Tunnels

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Abstract

To address the excessive rebound rate of shotcrete during tunnel construction, this study investigates the mix-proportion optimization and physico-mechanical properties of low-rebound shotcrete with an under-construction tunnel on the Cangtai Expressway as the engineering background. Three water-binder ratio levels (0.39, 0.42 and 0.45) were selected as the primary variable, while the sand ratio and unit water consumption were kept constant. Laboratory tests on slump and uniaxial compressive strength of shotcrete were carried out, and range analysis was utilized to quantify the effect of the water-binder ratio on the physico-mechanical performances of shotcrete. Field measurements were also performed to obtain the practical rebound rate under different water-binder ratio conditions. Experimental results reveal that the water-binder ratio is positively correlated with slump and negatively correlated with compressive strength. When the water-binder ratio increases from 0.39 to 0.45, the slump rises from 100 mm to 135 mm (an increment of 35%). The 7-day compressive strength decreases from 31.9 MPa to 22.3 MPa and the 28-day compressive strength declines from 38.2 MPa to 29.7 MPa, with reduction percentages of approximately 30.1% and 22.2%, respectively. the field-measured rebound rate first declines and then rises as the water-binder ratio increases. The lowest rebound-rate value is attained at a water-binder ratio of 0.42, where the slump equals 120 mm together with 7-day and 28-day compressive strengths of 27.1 MPa and 34.0 MPa. This mix balances construction pumpability, bearing capacity of the support and rebound suppression. This optimal mixture balances construction pumpability, bearing capacity of the support and rebound suppression. The research can furnish references for the mix-proportion design and construction of low-rebound shotcrete for tunnels.

Keywords

Low-rebound shotcrete; Mix-proportion optimization; Physical and mechanical properties; Laboratory testing; Field measurement.

1. INTRODUCTION

Shotcrete constitutes a critical element of the primary support system in mountain tunnels, and its construction quality plays a decisive role in controlling surrounding-rock deformation and ensuring support effectiveness. In recent years, wet-mix shotcreting has been increasingly adopted in highway tunnel projects because of its lower dust generation and higher construction efficiency. Nevertheless, excessive rebound remains a persistent problem in field applications. The adhesion of freshly sprayed concrete to the substrate is governed by multiple

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factors, including the characteristics of the constituent materials, fresh-state workability, surface conditions of the exposed rock, and spraying parameters. Under unfavorable conditions, coarse aggregate particles may rebound from the receiving surface, while cementitious paste may detach before adequate bonding is achieved. Excessive rebound not only increases material consumption and construction costs, but may also result in insufficient local lining thickness, thereby compromising the integrity and reliability of the initial support. Accordingly, the development of a mixture proportion compatible with site-specific materials and construction conditions is essential for minimizing rebound loss while maintaining the required mechanical and supporting performance.

To address excessive rebound and the continued reliance on empirical mixture design, researchers in China have investigated shotcrete from the perspectives of binder composition, early-strength systems, supplementary cementitious materials, and rebound measurement techniques. Yan et al.[1]optimized shotcrete mixtures by coordinating the particle-size distributions of cement, fly ash, and slag. Their results showed that a properly proportioned binder system could provide a satisfactory balance between fresh-state workability and mechanical performance. Liu et al.[2] reviewed the design criteria and engineering applications of early-high-strength shotcrete in railway tunnels and emphasized that mixture design should simultaneously satisfy pumpability, early-age strength, and field spraying requirements. Through laboratory proportioning tests followed by field validation, Gao et al.[3] developed C30 early-high-strength shotcrete, providing a material solution for primary tunnel support under complex geological conditions. Considerable attention has also been given to rebound mitigation and performance assessment. Yang et al.[4] proposed a rebound measurement method based on image-assisted three-dimensional reconstruction. By accounting for variations in the excavated tunnel profile, the method reduced the influence of overbreak geometry on rebound calculations. Yu et al.[5] combined nano-C-S-H seeds with an alkali-free accelerator to enhance fresh-state performance and early strength while maintaining a relatively low rebound rate under field conditions. Ma et al.[6] compared the effects of fly ash, silica fume, metakaolin, and carbon black on rebound, single-pass build-up thickness, and compressive strength. Their findings demonstrated that different mineral additions produced distinct trade-offs between rebound reduction and strength development. Li et al.[7] reported that rebound initially decreased and subsequently increased with increasing nano-C-S-H gel content, indicating that an optimum dosage range exists rather than a continuously beneficial response. International studies have placed greater emphasis on linking mixture design and rheological behavior with actual spraying performance. Ikumi et al.[8] systematically reviewed shotcrete proportioning approaches and noted that current standards generally prescribe limits for the water-to-binder ratio, binder content, and aggregate grading, whereas the final mixture is commonly determined through field spraying trials. Castellanos et al.[9] investigated the influence of viscosity-modifying admixtures on the yield stress, plastic viscosity, and thixotropy of wet-mix shotcrete and established relationships between laboratory rheological parameters and rebound measured during field application. Ning et al.[10] examined material transport during spraying and the subsequent deposition of wet-mix shotcrete on the receiving surface. Their results indicated that plastic viscosity governs the spreading and adhesion behavior of the material after impact, thereby affecting the spatial distribution and retention of the sprayed concrete.

Overall, previous studies have identified the principal factors governing shotcrete rebound through investigations of mixture proportioning, material modification, rheological characteristics, and spraying procedures. However, limited attention has been paid to the combined effects of the water-to-binder ratio on workability, compressive strength, and field rebound performance when locally available manufactured sand is used. Moreover, the total volume of shotcrete recorded during construction generally includes the material required to

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compensate for excavation overbreak. Consequently, calculating rebound solely from the difference between the recorded consumption and the theoretical design volume may lead to an overestimation of actual material loss. A more reliable assessment therefore requires the integration of laboratory performance tests, ring-by-ring construction records, and laser-scanned tunnel profiles. In view of this, based on the tunnel project of CTTJ10 section of Cangnan-Taishun Expressway, this paper uses local manufactured sand as fine aggregate and matches alkali-free liquid accelerator to carry out the research on the mix ratio of wet shotcrete. In this experiment, three groups of mix proportion levels were set up with water-binder ratio as the core control variable. The slump and compressive strength of wet-sprayed concrete mixture under different mix proportions were systematically tested in the laboratory. At the same time, three groups of different water-binder ratio schemes were carried out on-site spray construction test, and the rebound rate was measured and verified. The range analysis method is used to reveal the influence of water-binder ratio on the working performance, mechanical properties and on-site rebound characteristics of wet-sprayed concrete. Combined with the indoor performance index and on-site construction effect, the optimal mix ratio parameters suitable for the project are comprehensively optimized, in order to provide experimental support and technical reference for the mix ratio design and on-site construction control of shotcrete in this tunnel project.

2. TEST MATERIALS AND METHODS

2.1. Planning

P·O 42.5 ordinary Portland cement (C), supplied by Changshan Southern Cement Co., Ltd., was used as the primary binder in this study. Its principal physical and mechanical properties are summarized in Table 1. The residue retained on the 45 μm square-mesh sieve was 10.2%, while the water demand for normal consistency and the mortar flow value were 27% and 211 mm, respectively. The initial and final setting times were measured as 197 and 267 min. Soundness evaluated using the Le Chatelier method yielded an expansion value of 1.0 mm. All measured indices complied with the technical requirements specified in the Chinese standard Common Portland Cement (GB 175-2023). The mean flexural strengths at 3 and 28 days were 5.1 and 7.8 MPa, respectively, whereas the corresponding compressive strengths reached 28.1 and 51.1 MPa. These results indicate that the cement provided sufficient strength reserve for the preparation of the proposed wet-mix shotcrete.

Table 1. Physical and Mechanical Properties of Cement

Setting time/min		Compressive strength/MPa		Flexural Strength/MPa	
Initial setting	Final setting	3 d	28 d	3 d	28 d
197	267	28.1	51.1	5.1	7.8

Manufactured sand with a particle-size range of 0-4.75 mm, supplied by Changlong Mining Co., Ltd., was used as the fine aggregate (FA). The aggregate was clean and free from visible impurities. Particle-size distribution tests were performed in accordance with JTG 3432-2024. The grading curve, presented in Figure 1, fell within Zone II specified in JTG/T 3660-2020 and exhibited a continuous and well-proportioned distribution. The fineness modulus was 2.8, classifying the material as medium sand. These characteristics satisfied the quality requirements for fine aggregate used in tunnel shotcrete. Crushed stone with a particle-size range of 0-10 mm, also obtained from Changlong Mining Co., Ltd., was adopted as the coarse aggregate (CA). The material was clean and contained no apparent contaminants. Testing conducted in accordance with JTG 3432-2024 showed that the combined aggregate grading

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202609_12(9).0014

complied with the requirements of the Technical Code for Engineering of Ground Anchoring and Shotcrete Support (GB 50086-2015) and the project design specifications. As illustrated in Figure 2, the coarse aggregate had a nominal maximum size of 10 mm and maintained a continuous and stable particle-size distribution, making it suitable for wet-mix shotcrete placement.

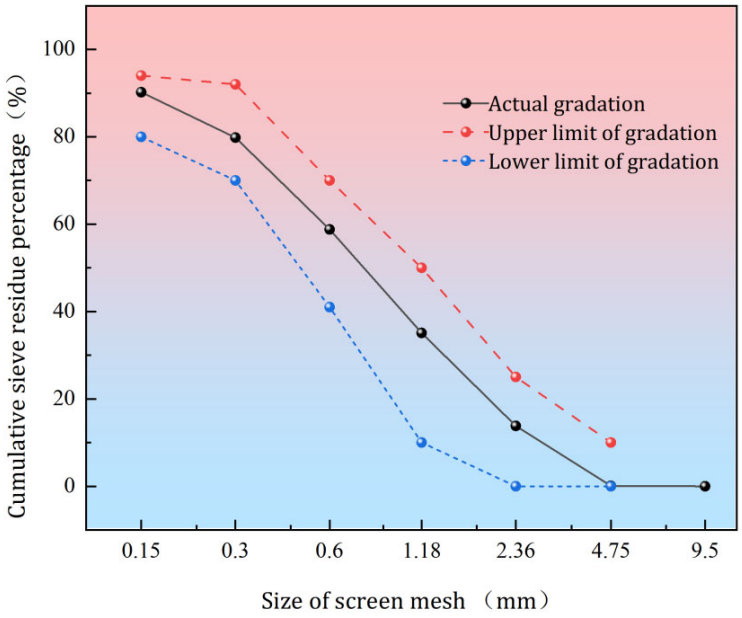


Figure 1. Gradation curve of fine aggregate

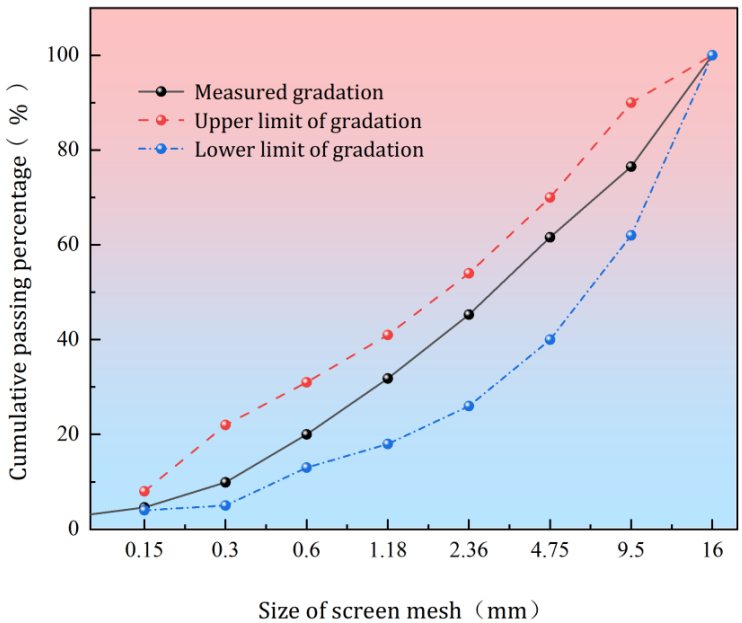


Figure 2. Gradation curve of coarse aggregate

The accelerator is a critical functional component of wet-mix shotcrete, as it governs both early-age strength development and the retention of mechanical properties at later ages. In this study, a ZJ-SNJ alkali-free liquid accelerator (SA), supplied by China West Construction New Materials Technology Co., Ltd., was incorporated at 7.0% by mass of the total binder. A polycarboxylate-based high-performance water-reducing agent (WR), manufactured by Beijing

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202609_12(9).0014

Building Construction Research Institute Co., Ltd., was also used at a dosage of 0.8% by mass of the binder.

2.2. Mix Proportion Design

The shotcrete mixture design and optimization were conducted with reference to the field conditions of wet-mix shotcreting in the tunnel works of the CTTJ10 contract section of the Cangnan-Taishun Expressway. The experimental program was developed in accordance with the relevant provisions of the Technical Code for Engineering of Ground Anchoring and Shotcrete Support (GB 50086-2015) and the Technical Specifications for Construction of Highway Tunnels (JTG/T 3660-2020). The water-to-binder ratio is a governing parameter for shotcrete because it directly affects strength development, compactness, and long-term durability. It also plays an important role in controlling pumpability, cohesiveness during spraying, and rebound behavior. Considering the specified strength grade and early-strength requirements of the tunnel support system, together with the practical demands of wet-mix shotcrete placement, the water-to-binder ratio was selected as the primary experimental variable. Three levels, namely 0.39, 0.42, and 0.45, were adopted to represent the range commonly used in engineering practice and to systematically evaluate its influence on the fresh and hardened properties of the shotcrete.

To isolate the effect of the water-to-binder ratio and ensure comparability among the mixtures, all other principal proportioning parameters were kept constant. The sand-to-total aggregate ratio was fixed at 53%, which was compatible with the grading characteristics of the manufactured sand used in this study. This proportion was selected to enhance mixture cohesiveness and water retention, thereby reducing aggregate rebound and dust generation during spraying. The unit water content was maintained at 194 kg/m^3 to provide a consistent baseline paste consistency for all mixtures.The water-reducing agent and accelerator were incorporated at constant percentages of the total binder mass. The former was used to regulate the initial flowability and pumpability of the fresh concrete, whereas the latter promoted rapid setting and early hardening after impact on the receiving surface. This approach ensured thatening after impact on the receiving surface. This approach ensured that all mixtures satisfied the workability requirements of field wet-mix shotcreting. Based on the selected water-to-binder ratios, the calculated binder contents for the three mixtures were 497, 462, and 431 kg/m^3 , respectively. The quantities of fine and coarse aggregates were subsequently determined using the absolute-mass proportioning method, and all constituent dosages complied with the relevant design specifications. The detailed mixture proportions of the three shotcrete mixtures are presented in Table 2.

Table 2. Mix proportion of shotcrete (kg/m^3)

Water-binder ratio	Cement	Coarse aggregate	Fine aggregate	Water	Super plasticizer	Set accelerator
0.39	497	780	879	194	3.98	34.79
0.42	462	796	898	194	3.7	32.34
0.45	431	811	914	194	3.45	30.17

2.3. Specimen Preparation and Test Methods

2.3.1. Specimen Preparation

Based on ' Technical code for geotechnical anchor and shotcrete support engineering ' (GB 50086-2015) and ' Technical code for highway tunnel construction (JTG / T 3660-2020), C25 concrete test block was prepared by normal scale construction technology. The 100 mm × 300 mm standard closed prism test block mold is selected in the test. The mold has sufficient rigidity

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202609_12(9).0014

and no deformation and slurry leakage, which meets the requirements of standard molding accuracy.

Before pouring the test block, the inner cavity of the mold was cleaned and the demoulding agent was evenly painted. The ingredients were strictly in accordance with the C25 concrete matching ratio, and the mixture was stirred by a forced mixer until the mixture was uniform and no segregation bleeding. The concrete is layered into the mold and fully vibrated until the surface is grouted and there are no obvious bubbles, so as to ensure that the test block is dense and complete, and there are no defects such as honeycomb and pockmarked surface. The pouring process is well protected to prevent debris from contaminating the sample. After pouring and forming, the sample is maintained in situ, and movement and disturbance are strictly prohibited within 18 h. During the period, coverage and watering are used to moisturize and maintain the early hydration of concrete. When the concrete is near the final setting, the surface is polished to ensure that the surface of the test block is flat and the corners are regular, which meets the requirements of the test molding. After curing for 1 d, the specimen was carefully removed to avoid bumping the damaged specimen. Immediately after removing the formwork, it was moved into the standard curing room and cured to 28 d age under the environment of temperature (20±2)° C and relative humidity ≥ 95 %. After the curing is completed, the specimen is repaired and processed, and then the mechanical performance test is carried out. The preparation and curing process of the sprayed concrete test sample is shown in Figure 3.

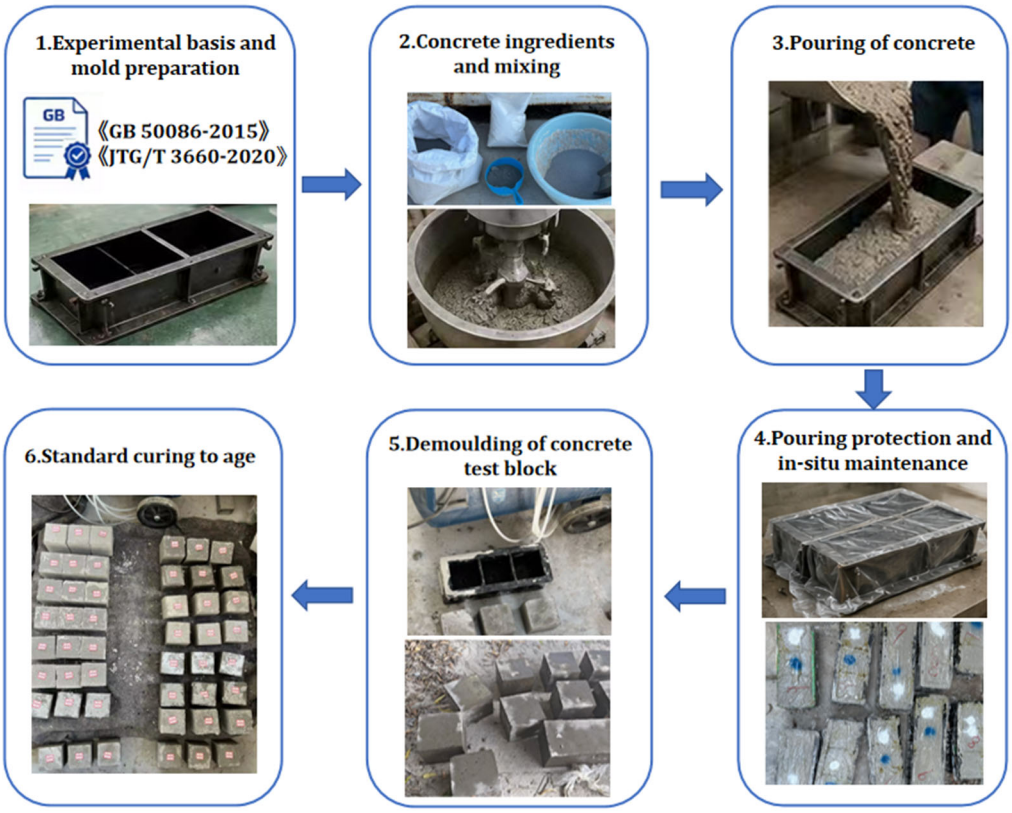


Figure 3. Preparation and curing process of shotcrete test specimens

2.3.2. Physical and Mechanical Property Tests

(1) Slump Test

Slump is the core index to characterize the fluidity of fresh concrete and evaluate the pumpability, which directly determines the smoothness of wet shotcrete pipeline

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202609_12(9).0014

transportation and the quality of on-site shotcrete construction This test was carried out according to the " Standard for Testing Methods for Performance of Ordinary Concrete Mixtures " (GB / T 50080-2016), and the slump values of machine-made sand wet shotcrete under different water-binder ratios were tested. Before the test, the equipment such as the calibration slump cylinder, the standard ram rod, and the rigid steel plate bottom plate are cleaned. The test instrument is shown in Figure 4.



Figure 4. Slump cone

Before the start of the test, ensure that the inner wall of the slump cylinder is smooth without attachment, and the bottom plate is flat without water accumulation ; according to the target mix proportion, the cementitious material, machine-made sand, coarse aggregate, mixing water and alkali-free accelerator are accurately weighed. The test environment temperature is stabilized at 20±5°C, and the flow deviation caused by temperature and humidity fluctuation is reduced. When mixing, the coarse and fine aggregates and the cementitious materials are first put into the mixer for dry mixing for 30 s, and then wet mixing for 120 s after adding all the mixing water. The alkali-free accelerator is uniformly mixed at 10 s before unloading and then stirred for 10 s. After the mixing is completed, the test is immediately discharged. The standing time of the whole mixture is not more than 2 min, so as to avoid the accelerator to trigger the condensation effect in advance to interfere with the test results.

During the test, the slump cylinder is fixed at the center of the bottom plate, and the mixture is filled in three layers, each layer is about 1 / 3 of the height of the cylinder ; each layer is evenly mashed 25 times from outside to inside along the spiral line. The bottom layer is mashed to the bottom plate, and the upper layer is inserted into the lower layer 10-20 mm. After leveling the mouth of the cylinder, the surrounding surplus material is removed, and the cylinder is lifted at a vertical uniform speed within 5-10 s without lateral shaking. After the lifting cylinder is completed, the vertical height difference between the top of the cylinder and the highest point of the mixture is measured immediately. If the sample collapses on one side and is seriously separated, the test is invalid. Each group of mix ratios is subjected to two parallel tests. When the difference is less than or equal to 10 mm, the arithmetic mean is taken as the final slump value.

(2) Compressive Strength Test

In this test, according to GB / T 50081-2019 ' Standard for Testing Methods of Physical and Mechanical Properties of Concrete' and GB 50086-2015' Technical Specification for Geotechnical Anchor and Shotcrete Support Engineering ', the specimens were prepared by concrete pouring method and 7d and 28d compressive strength tests were carried out to evaluate the mechanical properties of shotcrete. The test process is shown in Figure.5.

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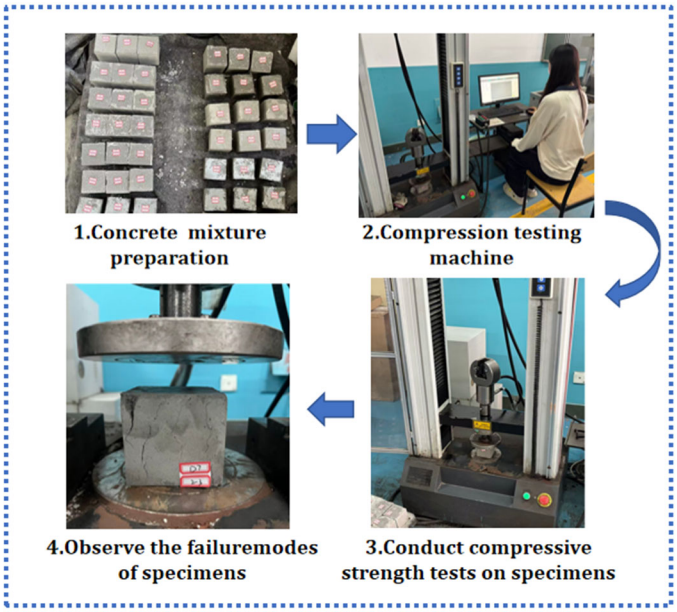


Figure 5. Flow chart of shotcrete compressive strength test

The loading process of the test block adopts a continuous and uniform loading system, and the loading rate is controlled at 0.5-0.8MPa / s until the specimen is obviously damaged, and the ultimate failure load is recorded. After the loading is completed, the crack propagation path and the final failure mode of the specimen are observed and recorded. The cubic compressive strength of the specimen is calculated according to Formula 2-1 :

$$f_{cc} = \frac{F}{A} \tag{2-1}$$

In the formula: fcc is the compressive strength of shotcrete cube, MPa ; F is the ultimate failure load of the specimen, N ; A is the bearing area of the specimen, mm^2 ;

2.3.3. Shotcrete rebound rate test

Rebound rate is an important index to evaluate the material loss of shotcrete, the adhesion performance of sprayed surface and the construction economy. Different from the performance indexes such as slump and compressive strength that can be standardized under indoor conditions, the rebound rate of shotcrete is not only affected by the mix ratio parameters, but also closely related to the on-site construction conditions such as the surface flatness of surrounding rock, spraying position, spraying distance, working wind pressure, equipment performance and spraying hand operation level. Therefore, in order to evaluate the rebound control effect of different water-binder ratio mix ratios under the actual tunnel wet spraying construction conditions, this paper does not set up the indoor standard spray rebound test, but uses the on-site construction data accounting method to carry out engineering verification.

The on-site verification is based on the large rock tunnel exit section of the CTTJ10 section of the Cangnan-Taishun Expressway. The three groups of water-binder ratio schemes determined by indoor test are applied to the field shotcrete construction, and the corresponding pile number, lining type, construction site, water-binder ratio, design shotcrete volume and actual concrete use volume are collected ring by ring according to the construction cycle. At the same time, the excavation contour and average over-excavation thickness of each construction ring are obtained by laser profiler, which is used to calculate the concrete filling amount required for the over-excavation part of surrounding rock. The actual amount of sprayed concrete used in the field mainly includes the designed amount of sprayed concrete, the over-excavation filling

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amount of surrounding rock, and the rebound and construction loss during the spraying process. If the rebound rate is calculated directly by the difference between the actual use amount and the designed spray volume, the over-excavation filling amount with supporting effect will be included in the rebound loss, thus overestimating the rebound level of shotcrete. Therefore, in this paper, the amount of surrounding rock over-excavation filling is deducted from the actual over-consumption, and the on-site rebound rate is corrected and calculated.

Calculation principle: The total over-consumption of shotcrete on site consists of two parts: one is the effective attachment amount to fill the over-excavation depression of surrounding rock, and the other is the rebound drop and a small amount of construction loss during the spraying process. Therefore, the real rebound rate needs to deduct the amount of over-excavation filling from the total over-consumption, and then calculate its proportion in the actual total injection volume. The calculation formula is :

$$\eta = \frac{V_s - V_d - V_o}{V_s} \times 100\% \tag{2-2}$$

$$V_o = V_d \times \frac{\bar{t}}{d} \tag{2-3}$$

In the formula : Vs is the actual use of single-ring shotcrete (m^3) ; Vd is the design jet volume (m^3) of the corresponding lining type ; Vo is the concrete filling volume (m^3) corresponding to the single-ring overbreak ; t is the average overbreak thickness of single ring (m) ; d is the designed shotcrete thickness (m) of the corresponding lining type.

3. ANALYSIS OF EXPERIMENTAL RESULTS

3.1. Analysis of the Physical Properties of Shotcrete

The variation of concrete slump under different water-binder ratios is shown in Fig.6. On the whole, the slump increases linearly with the increase of water-binder ratio, and the water-binder ratio is the core parameter to control the flow performance of fresh concrete.

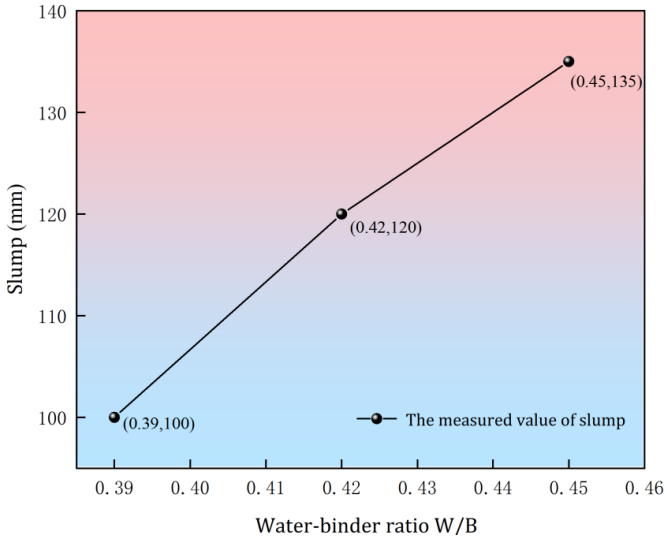


Figure 6. Relationship curve between slump and water-binder ratio W / B

From the specific numerical changes, when the water-binder ratio increases from 0.39 to 0.45, the concrete slump increases from 100 mm to 135 mm, an increase of 35 %. The internal

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202609_12(9).0014

mechanism of this law is as follows: under the condition that the amount of cementitious material and aggregate gradation remain unchanged, the increase of water-binder ratio means that the amount of free mixing water in unit volume concrete increases, and the proportion of slurry volume increases. The excess slurry can fully wrap the aggregate surface to form a lubricating layer, reduce the friction resistance between the aggregate particles, and fill the aggregate gap to improve the overall deformation and flow capacity of the mixture. Therefore, the slump continues to increase with the increase of water-binder ratio.

In order to quantify the influence of water-binder ratio on the physical properties of shotcrete, the range analysis method was used to process the test results. The slump was used as the evaluation index to calculate the mean value ki and range R at each water-binder ratio level. The analysis results are shown in Table 3. Among them, the range R reflects the influence of the level fluctuation of the factor on the index. The larger the R value is, the more significant the regulation effect of the factor on the evaluation index is.

Table 3. Shotcrete slump range analysis results

Evaluating indicator	k_1	k_2	k_3	Range	The optimum level
Slump/mm	100	120	135	35.0	A_2

It can be seen from Table 3 that as the water-binder ratio increases from 0.39 to 0.45, the slump of the shotcrete mixture shows a monotonous upward trend, with a range of 35.0 mm, indicating that the water-binder ratio has a significant regulatory effect on the fluidity of the mixture. The mechanism of action is that the increase of water-binder ratio increases the free water content in the system, reduces the viscosity of cement paste, enhances the lubrication and wrapping effect of machine-made sand and gravel aggregate, effectively reduces the friction resistance between particles, and continuously improves the flow performance of the mixture.

3.2. Analysis of Mechanical Properties of Shotcrete

Under the condition of different water-binder ratio, the change rule of 7d and 28d compressive strength of shotcrete is shown in figure 7. On the whole, the compressive strength of shotcrete at two ages decreases linearly with the increase of water-binder ratio, and the strength of 28d is always significantly higher than that of 7d, which is in line with the basic law of concrete strength development.

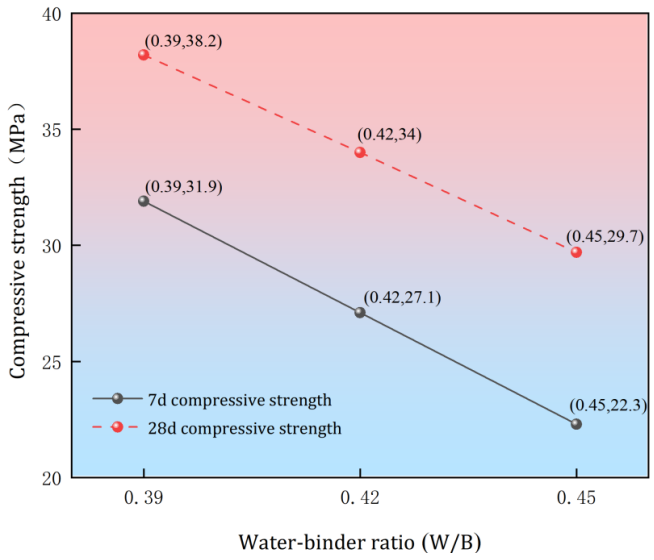


Figure 7. Relationship curve between compressive strength and water-binder ratio W / B

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202609_12(9).0014

From the change of strength value, when the water-binder ratio is 0.39,0.42 and 0.45, the 7 d compressive strength of shotcrete is 31.9 MPa,27.1 MPa and 22.3 MPa respectively, and the 28 d compressive strength is 38.2 MPa,34.0 MPa and 29.7 MPa respectively. When the water-binder ratio increased from 0.39 to 0.45, the 7d compressive strength decreased by 9.6 MPa, a decrease of 30.1 % ; the 28 d compressive strength decreased by 8.5 MPa, a decrease of 22.3 %. When the water-binder ratio increased from 0.39 to 0.42, the compressive strength of 7d and 28d decreased by 4.8 MPa and 4.2 MPa, respectively. When the water-binder ratio is further increased from 0.42 to 0.45, the compressive strength of the two ages is reduced by 4.8 MPa and 4.3 MPa, respectively. It can be seen that within the scope of this test, for every 0.03 increase in water-binder ratio, the compressive strength of shotcrete at 7d and 28d decreases steadily, indicating that water-binder ratio is an important mix ratio parameter affecting the strength development of mechanism sand wet shotcrete.

From the perspective of strength development at different ages, when the water-binder ratio is 0.39,0.42 and 0.45, the 7d compressive strength reaches 83.5 %, 79.7 % and 75.1 % of the corresponding 28d compressive strength, respectively. It shows that the three groups of shotcrete have a faster early strength development speed, but with the increase of water-binder ratio, the proportion of 7d strength to 28d strength gradually decreases, and the early strength development degree is weakened. This is because the concentration of cement particles in unit volume is higher under the condition of low water-binder ratio, and the early hydration products can be formed quickly under the action of alkali-free accelerator, which makes the concrete structure set and harden rapidly, so the 7d strength is higher.

In order to quantify the influence of water-binder ratio on the mechanical properties of shotcrete, the range analysis method is used to process the test results. The 7d and 28d cube compressive strength is used as the evaluation index, and the index mean ki and range R under each water-binder ratio level are calculated. The analysis results are shown in table 4. Among them, the range R reflects the influence of the level fluctuation of the factor on the index. The larger the R value is, the more significant the regulation effect of the factor on the evaluation index is.

Table 4. The range analysis results of 7d and 28d compressive strength of shotcrete

Evaluating indicator	k_1	k_2	k_3	Range	The optimum level
7d compressive strength/MPa	31.9	27.1	22.3	9.6	A_1
28d compressive strength/MPa	38.2	34.0	29.7	8.5	A_1

The results of range analysis show that the compressive strength of shotcrete at 7d and 28d decreases monotonously with the increase of water-binder ratio in the test range of 0.39-0.45. When the water-binder ratio increased from 0.39 to 0.45, the 7d compressive strength decreased from 31.9 MPa to 22.3 MPa, with a decrease of 30.1 %. The 28 d compressive strength decreased from 38.2 MPa to 29.7 MPa, with a decrease of 22.3 %. For every 0.03 increase in water-binder ratio, the compressive strength of 7 d decreased by 4.8 MPa, and the compressive strength of 28 d decreased by 4.2 MPa and 4.3 MPa, respectively, indicating that the compressive strength decreased steadily with the increase of water-binder ratio in the test range. The range of 7d and 28d compressive strength is 9.6MPa and 8.5MPa respectively, which reflects that there are great differences in strength between the two ages under different water-binder ratio levels. Among them, the absolute range and relative decrease of 7d compressive strength are greater than that of 28d compressive strength, indicating that the response of 7d strength to the change of water-binder ratio is more obvious. The reason is that with the increase of water-binder ratio, the proportion of water in the slurry relative to the cementitious material increases. At the same time, under the condition that the unit water consumption remains unchanged, the amount of

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202609_12(9).0014

cementitious material decreases accordingly. After hardening, the capillary pores and interfacial transition zone defects in the slurry increase, and the compactness of the concrete decreases, resulting in a decrease in compressive strength. Because the compressive strength is a positive evaluation index, under the condition of only considering the compressive strength of 7 d and 28 d, the A1 level corresponding to the water-binder ratio of 0.39 is better ; however, the final determination of the mix ratio still needs to be comprehensively evaluated in combination with the working performance and the on-site rebound control effect.

3.3. Calculation and Analysis of Field Rebound Rate

In order to accurately reveal the regulation law of water-binder ratio on the rebound characteristics of shotcrete and eliminate the influence of interference factors such as over-excavation of surrounding rock, construction site and section type, this study selected three typical lining sections covering SA4 a, SA3 JQ and SA3 a from the cumulative 240-ring construction ledger of the left and right holes of the tunnel, including the upper step arch and the whole section. The representative ring numbers with complete over-excavation data and stable construction conditions are used to calculate the rebound rate. The samples take into account different surrounding rock levels and construction methods, and have sufficient engineering representativeness. Combined with the adjustment process of the project construction mix ratio, the selected samples correspond to the three water-binder ratio levels of the indoor test : the initial stage of construction corresponds to the water-binder ratio of 0.39 (focusing on strength reserve), the medium-term optimization stage corresponds to the water-binder ratio of 0.42 (balance strength and construction), and the later pumping adjustment stage corresponds to the water-binder ratio of 0.45 (improving flow performance). Three representative ring numbers are selected in each group, and the real springback rate formula described in section 2.3.3 is used for calculation. The results are shown in the table.

According to Article 7.2.10 of ' Technical Specification for Highway Tunnel Construction ' (JTG/T 3660-2020), the rebound rate of wet shotcrete construction should meet the following requirements : the rebound rate of arch should not be greater than 25 %, and the rebound rate of side wall should not be greater than 15 %. A total of 9 groups of representative construction rings with complete data and stable working conditions in the left and right holes were selected to calculate the real rebound rate. The results are shown in the table 5.

Table 5. Calculation results of rebound rate of shotcrete in representative construction ring

Water-binder ratio	Corresponding Ring number	Design volume /m³	Actual dosage /m³	Average overcut Thickness /cm	Over-digging filling Square quantity/m³	Percentage of rebound/%
0.39	Left hole Z14	15.8	38.5	16	11.49	29.1
0.39	Left hole Z16	15.8	38.5	16	11.49	29.1
0.39	Left hole Z18	15.8	42.5	16	11.49	36.3
0.42	Left hole Z19	11.9	34.0	16	8.65	19.0
0.42	Left hole Z22	11.9	36.5	19	10.28	11.6
0.42	Left hole Z26	11.9	32.5	20	10.82	17.8
0.45	Left hole Z121	24.8	50.0	12	13.53	23.3
0.45	Left hole Z123	24.8	51.0	13	14.65	22.6
0.45	Left hole Z124	24.8	60.0	11	12.4	26.9

Note : The design spray layer thickness is based on the tunnel lining design document of this project : the grade IV surrounding rock SA4a is 22cm, and the grade III surrounding rock SA3JQ / SA3a is 15cm ;

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202609_12(9).0014

It can be seen from the calculation results that the water-binder ratio has a significant nonlinear control effect on the real rebound rate of shotcrete, and the overall trend is to decrease first and then increase. There is a clear optimal water-binder ratio interval. Reasonable regulation of water-binder ratio can have a significant positive effect on rebound control : the average rebound rate in the low water-binder ratio (0.39) group is 31.5 %, which exceeds the limit of 'arch rebound rate should not be greater than 25 % ' stipulated in the ' Highway Tunnel Construction Technical Specification ' (JTG / T 3660-2020). The mechanism is that the viscosity of the slurry is large and the workability deviation is low under low water-binder ratio. The cement slurry has insufficient lubrication effect on the mechanism sand and gravel aggregate, and the aggregate particles are easy to rebound and fall off due to collision during the injection process. At the same time, the fluidity of the slurry is weak, and the stability of the pumping flow is poor, which further aggravates the rebound loss. The average rebound rate in the group with the optimal water-binder ratio (0.42) is reduced to 16.2 %, which is far lower than the specification limit. The rebound control effect is the best, which is 15 percentage points lower than the rebound rate of 0.39 group, and the material loss is reduced by nearly 46 %. Under this water-binder ratio, the fluidity and cohesion of the slurry achieve the best balance, and the micro-aggregate filling effect of the machine-made sand powder and the coagulation effect of the alkali-free accelerator form a coupling gain : on the one hand, an appropriate amount of stone powder optimizes the slurry gradation and improves the adhesion performance of the slurry ; on the other hand, the accelerator can quickly trigger the setting and hardening of the slurry after injection, effectively inhibiting the flow and shedding of the spray layer, so the rebound rate is significantly reduced. The average rebound rate in the high water-binder ratio (0.45) group rose to 24.3 %. Although it still met the specification requirements, it increased by 7.2 percentage points compared with the optimal water-binder ratio. The reason is that when the water-binder ratio is too high, the slurry dilution leads to a decrease in cohesion, the accelerating reaction of the accelerator is diluted by free water, and the setting hardening rate slows down. After being sprayed onto the surface of the surrounding rock, it is easy to flow and fall, which eventually leads to an increase in rebound rate and material loss.

3.4. Comprehensive Optimization of Mix Proportion Parameters

Combined with the design requirements of tunnel support in CTTJ10 section of Cangtai Expressway and the construction conditions of wet spraying on site, different water-binder ratio schemes are comprehensively compared and selected from three aspects: working performance, mechanical properties and rebound control effect on site. When the water-binder ratio is 0.39, the 28 d compressive strength of shotcrete is 38.2 MPa, which is the highest among the three groups, but the slump is only 100 mm. The fluidity of the mixture is relatively low, which may increase the pipeline transportation resistance and the risk of pipe blockage. After deducting the over-excavation filling amount of surrounding rock, the average rebound rate on site is 31.5 %, which is higher than the requirement that the rebound rate of wet shotcrete arch should not be greater than 25 % stipulated in the specification, and the rebound loss is large. When the water-binder ratio was 0.45, the slump increased to 135 mm, the fluidity of the mixture was better, and the 28 d compressive strength was 29.7 MPa. Although it met the design strength grade requirements, the strength reserve was lower than that of 0.39 and 0.42 groups. The average rebound rate on site is 24.3 %, which is significantly higher than that of 0.42 group and close to the standard control value. In contrast, when the water-binder ratio is 0.42, the slump is 120 mm, which has good construction adaptability, and the 28 d compressive strength is 34.0 MPa, which can meet the design strength requirements and retain a certain strength reserve. The average rebound rate was 16.1 %, which was the lowest in the three groups, which was 15.4 percentage points lower than that in the 0.39 group. Considering the working performance, mechanical properties and rebound control effect, the comprehensive

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202609_12(9).0014

performance of water-binder ratio 0.42 is the best under the range of test parameters and on-site construction conditions. It is recommended as the suitable water-binder ratio for wet shotcrete in this project.

4. CONCLUSIONS

(1) The water-binder ratio has a significant positive correlation with the slump of fresh manufactured-sand wet-process shotcrete. Within the test range of 0.39-0.45, as the water-binder ratio increases from 0.39 to 0.45, the slump of the mixture rises linearly from 100 mm to 135 mm, with an overall increment of 35%. The slump range value reaches 45.0 mm, indicating that the water-binder ratio acts as the core governing parameter for the pumpability of wet-process shotcrete. A low water-binder ratio can markedly increase the pipeline transportation resistance and raise the risk of pipe blockage.

(2) The water-binder ratio exhibits a notable negative correlation with the 7-day and 28-day compressive strengths of shotcrete. When the water-binder ratio increases from 0.39 to 0.45, the 7-day compressive strength declines from 31.9 MPa to 22.3 MPa, with a reduction of 30.1%, while the 28-day compressive strength drops from 38.2 MPa to 29.7 MPa, corresponding to a 22.3% decrease. The range value of 7-day compressive strength reaches 9.6 MPa, which is greater than the 28-day-strength range of 8.5 MPa. This demonstrates that the early-age strength possesses higher sensitivity to variations in the water-binder ratio.

(3) The rebound rate of shotcrete exhibits a nonlinear tendency to decrease first and then increase as the water-binder ratio rises. At a water-binder ratio of 0.39, the field-measured average rebound rate is 31.5%, which exceeds the limit of 25% for the crown rebound rate of wet-process shotcrete stipulated by Technical Specifications for Construction of Highway Tunnel (JTG/T 3660-2020). When the water-binder ratio is increased to 0.42, the average rebound rate falls to 16.1%, approximately 15.4% lower than that of the 0.39 group. This demonstrates that the slurry achieves a favourable balance of fluidity, cohesiveness and adhesion to the receiving surface. A further increase in the water-binder ratio to 0.45 raises the free-water content of the mixture and impairs slurry cohesiveness, and consequently the average rebound rate rebounds to 24.3%. With comprehensive consideration of construction workability, mechanical performance and material-waste control, a water-binder ratio of 0.42 is recommended as the optimum value for low-rebound wet-process shotcrete in this tunnel project.

KNOWLEDGMENTS

The authors wish to express their sincere gratitude to the China State Construction Engineering Corporation Project (Project No. JTZB-CTGS10-D194/2025) for its financial backing and to the reviewers for their insightful feedback, both of which were invaluable to this work.

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