CONSTRUCTION METHOD FOR LOW-REBOUND SHOTCRETE

Field of the Invention

The present invention pertains to the technical field of concrete spraying, and more specifically, relates to a construction method for low-rebound shotcrete.

Background to the Invention

With the continuous development of high-grade highways and high-speed railway construction, the proportion of tunnels in the route is increasing. Tunnel engineering is different from other projects and is difficult to repair. This requires the tunnel structure to have sufficient durability. As shotcrete is located between the surrounding rock and the secondary lining, once its durability fails, it cannot be repaired. Therefore, the performance of shotcrete should be given sufficient attention. Since it is in direct contact with the surrounding rock and groundwater, it is susceptible to dissolution and chemical erosion. Thus, improving the compactness of concrete is the key. At present, ordinary Portland cement is still commonly used in shotcrete, with a single composition and low quality, resulting in poor compactness of the concrete, weak resistance to carbonation and erosion, and insufficient durability. Shotcrete is applied promptly after tunnel excavation, so it bears loads at an early stage, requiring sufficient early strength, which is fundamentally different from cast-in-place concrete. Currently, dry-mix shotcrete still dominates in China, with the vast majority of cement being ordinary Portland cement, which is costly and ineffective, necessitating bold and diversified attempts.

There are significant differences between the construction technology, conditions, and technical level of workers in shotcrete construction and the performance indicators of commercially available accelerators on the market. This leads to a high rebound rate during shotcrete construction, which not only increases material waste but also results in major defects in engineering quality. It also endangers the safety of on-site construction personnel and fails to meet national requirements for energy conservation, emission reduction, and carbon reduction. Controlling the rebound rate in shotcrete construction is an urgent issue the industry must address. At present, the comprehensive rebound rate of ordinary C20–C30 dry-mix or wet-mix shotcrete used for sidewalls and crown arches in underground cavern support for hydropower, water conservancy, railway, and highway projects is generally high. Moreover, the strength of dry-mix shotcrete often fails to meet standards. The rebound rate of dry-mix shotcrete is generally above 20%, and can even reach 40%–50%, while the rebound rate of wet-mix shotcrete also frequently exceeds 20%. This significantly increases construction costs and prolongs the duration of shotcrete support.

Statement of Invention

To overcome the deficiencies in the existing technology mentioned above, the present invention provides a construction method for low-rebound shotcrete. This method ensures the strength of the concrete, provides excellent spraying homogeneity, achieves high productivity, produces virtually no dust during construction, results in low rebound rate. The liquid accelerator may be automatically metered and added to the spray nozzle according to the concrete discharge volume. Through the mixing effect of high-flow compressed air, the wet concrete mixture is more easily and thoroughly blended. The wet-sprayed layer is uniformly applied, rapidly sets and hardens, and adheres firmly to the tunnel substrate through strong bonding with the rock bolts and mesh, forming a support layer with certain load-bearing capacity.

To address the aforementioned technical problems, the technical solutions adopted by the present invention are as follows.

A construction method for low-rebound shotcrete includes the following steps:

S1. selecting raw materials for shotcrete and preparing the shotcrete;

S2. designing the concrete mix proportion;

S3. mixing the concrete: using a fully automatic metering forced mixer for wet-mix shotcrete;

S4. transporting the concrete: using concrete transport tankers for transportation, continuous mixing the concrete in the transportation process; when spraying the concrete, a plurality of transport vehicles alternately delivering materials to ensure sufficient supply of wet-mix shotcrete;

S5. preparation before spraying: inspecting the excavation cross-section dimensions, removing loose debris, and cleaning the surface to be sprayed;

S6. performing shotcrete construction;

S7. conducting curing: starting curing 2 hours after the final setting of shotcrete;

S8. performing quality inspection;

S9. measuring rebound rate.

In step S1, the raw materials for concrete include: cement: selecting the type of cement based on the project environment and project requirements; fine aggregate: apparent density of the fine aggregate ≥2500 kg/m^3, water absorption ≤3.5%, for shotcrete requiring frost resistance, the mass loss of the fine aggregate in freeze-thaw testing ≤10%, clay lumps ≤1.0, chloride ion content ≤0.02; coarse aggregate: apparent density of the coarse aggregate ≥2500 kg/m^3, water absorption ≤3.5%, for shotcrete requiring frost resistance, the mass loss of the coarse aggregate in freeze-thaw testing ≤12%, clay lumps ≤0.25; limestone micro-powder: harmful clay content ≤1.2 g/100 g, $CaCO_3$ content ≥95%, CaO ≥53.2%, specific surface area ≥3000 cm^2/g; silica fume: moisture content ≤3%; other admixtures: including slag micro-particles, activated clay, volcanic ash micro-powder, and ettringite-based synthetic admixture;

accelerator: including methyl sulfoxide-modified sepiolite and aluminum salt, obtained with modified polyhydroxy-alkylamine added and reacted in a reaction kettle for 3 hours;

nano spray rebound-reducing agent for concrete: prepared by polymerizing acrylamide, acrylic acid, and acrylonitrile monomers in an aqueous solution in the presence of a water-soluble free radical initiator, with a reaction temperature of 30-70°C for 2-7 hours, followed by neutralization and hydrolysis reactions at 50-70°C to obtain an acrylamide-acrylate-acrylonitrile terpolymer with a viscosity of 0.60-7.00 Pa·s for a 5 wt.% aqueous solution at 25°C.

In step S2, the compactness of shotcrete is determined based on the comprehensive environmental grade, followed by selecting the binder formula according to compactness indicators; the strength grade of shotcrete is determined based on the surrounding rock grade, followed by selecting the concrete mix proportion according to the strength grade.

In step S3, putting the prepared cementitious material, sand, and 1/3 of the water into the mixer for pre-mixing for 30 s; then adding the water reducer to the remaining water, mixing uniformly, and putting the mixture combined with all coarse aggregate into the mixer for mixing for 90 s.

In step S5, treating the rock surface to be sprayed before spraying by washing away loose dust and rock chips on the rock surface to be sprayed with high-pressure water; when the rock surface is deliquesced or argillized by water, using high-pressure air to clean the rock surface; for muddy or sandy rock surfaces, installing a fine steel mesh fixed with circumferential rebar, anchor nails, or directly onto the steel frame to ensure close contact with the surface to be sprayed for improved shotcrete adhesion; before spraying the concrete, first spraying a layer of cement mortar, and then spraying the concrete after the final setting.

In step S6, setting markers to control shotcrete thickness by embedding rebar heads as indicators and inserting iron wires 5 cm longer than the design thickness at 1-1.5 m intervals in spraying for construction control;

inspecting machinery, equipment, and pipelines for air, water, and electricity; using an Aliva wet-mix shotcrete machine unit for the concrete spraying construction, positioning the wet-mix shotcrete machine, and conducting trial operation; adjusting the spraying volume via a handwheel after starting the wet-mix shotcrete machine motor, with real-time adjustments in spraying based on air volume and spraying requirements displayed on the screen menu; for the liquid accelerator, entering the mix proportion menu and setting the accelerator addition amount at 2% of the cement dosage per cubic meter of concrete;

in the construction process of shotcrete, premixed concrete is mixed with the accelerator near the nozzle and then instantly sprayed onto the base layer, with the mixing and spraying process lasting less than 1 minute.

In step S6, the spraying sequence is to spray the wall first and then the arch, from bottom to top, moving in an S-curve; starting spraying from the bottom of the sidewalls on both sides of the tunnel and closing at the centerline of the arch crown to complete a trial spraying of a ring of shotcrete;

keeping the nozzle perpendicular to the surface in spraying; when spraying perpendicular to the rock surface, the continuous “thin flow” of concrete has a secondary embedding effect on the rebound materials, reducing rebound rate and increasing single-layer thickness; and

maintaining a distance between the nozzle and the rock surface of 1-1.5 m.

In step S6, first extending the boom of the manipulator to adjust the spraying position of the nozzle at the bottom of the sidewall, using the automatic parallel function of the forearm of the manipulator to adjust the forearm to be horizontal to the ground and parallel to the sidewall of the tunnel, then adjusting the nozzle distance and angle; after completing the above work, commencing spraying without further adjustments to nozzle distance, angle, or the boom of the manipulator in spraying, only using the automatic extension function to control the nozzle to automatically extend and retract on the forearm, that is, slowly move from one end to the other end and back 2-3 times to complete one spraying; then extending the boom by 30 cm, moving the boom vertically and horizontally to ensure the angle and distance between the nozzle and the rock surface, and spraying the next part in the above-mentioned sequence, repeating this cycle to complete the spraying of the surface to be concreted.

In step S7, adopting spray-based curing for rock tunnels and liquid curing agents for loess tunnels, with a curing duration ≥14 days; prohibiting water curing when temperatures are below +5°C.

In step S9, employing 3D laser scanning for detection, acquiring high-precision station information and 3D models of the working face pre-/post-spraying via 3D laser scanning technology combined with multi-modal fusion station technology, aligning the positions of the solid models in two time dimensions in the same spatial system, converting projections to obtain high-density 2D cross-sections, and calculating the formed volume of the shotcrete via 2D section comparison to derive rebound volume from total sprayed volume.

Compared with the prior art, the present invention has the following advantages.

The characteristics of wet-mix shotcrete are that the strength of the construction concrete is guaranteed, the spraying homogeneity is good, the productivity is high, there is basically no dust during construction, and the rebound rate is low. The liquid accelerator may be automatically metered and added to the spray gun according to the concrete discharge volume. Through the mixing effect of high-flow compressed air, it is easier for the wet-mix concrete to fully mix, resulting in uniform wet-spray layers that rapidly set and harden. By firmly bonding with the rock bolts and mesh reinforcement, it adheres to the tunnel substrate, forming an initial support lining layer with certain load-bearing capacity. The shotcrete construction does not experience spalling, achieving the effect of rapid support. During construction, due to its rapid-setting effect, the rebound rate may be reduced to below 5%. Its high water-reducing property allows for a reduction in unit water consumption while maintaining slump, lowering the water-to-binder ratio, thereby effectively controlling overall construction costs. Additionally, this spray mixture may fill the pores of cement, increasing the packing density of the cement paste. Sufficient paste fills the void spaces in the concrete, coating and lubricating aggregate particles, reducing internal friction in the mixture, and enhancing cohesion, fluidity, and plasticity of the mixture, thereby improving the workability of the concrete. It also blocks the capillary pores in the concrete, reducing bleeding in shotcrete and improving durability properties such as impermeability and corrosion resistance. Using a manipulator for wet-mix shotcrete operations reduces the labor intensity for construction personnel, minimizes occupational hazards, and significantly improves work efficiency during wet-mix spraying.

Brief Description of the Drawings

FIG. 1 is a schematic diagram of a construction process of the present invention; and

FIG. 2 is a schematic diagram of the wet-mix spraying process in the present invention.

Detailed Description

To enable a clearer understanding of the aforementioned objectives, features, and advantages of the present invention, the following provides a further detailed description of the invention in conjunction with the accompanying figures and specific examples. It is to be noted that, in the absence of conflict, the examples of the present invention and the features within the examples may be combined with each other.

In the following description, numerous specific details are set forth to facilitate a thorough understanding of the present invention. However, the present invention may also be implemented in other ways different from those described herein. Therefore, the scope of protection of the present invention is not limited by the specific examples disclosed below.

As shown in FIG. 1 and FIG. 2, a construction method for low-rebound shotcrete includes the following steps:

S1. selecting raw materials for shotcrete and preparing the shotcrete;

S2. designing the concrete mix proportion;

S3. mixing the concrete: using a fully automatic metering forced mixer for wet-mix shotcrete;

S4. transporting the concrete: using concrete transport tankers for transportation, continuous mixing the concrete in the transportation process; when spraying the concrete, a plurality of transport vehicles alternately delivering materials to ensure sufficient supply of wet-mix shotcrete;

S5. preparation before spraying: inspecting the excavation cross-section dimensions, removing loose debris, and cleaning the surface to be sprayed;

S6. performing shotcrete construction;

S7. conducting curing: starting curing 2 hours after the final setting of shotcrete;

S8. performing quality inspection;

S9. measuring rebound rate.

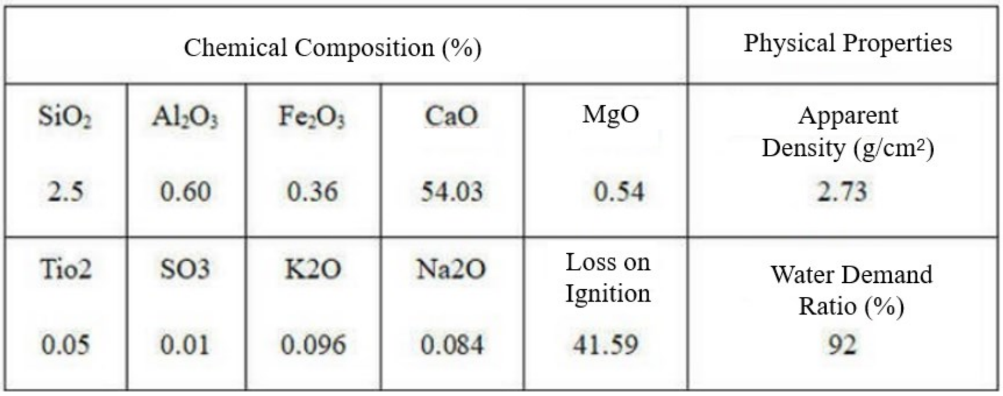
Preferably, in step S1, the raw materials for concrete include: cement: the type of cement is selected mainly based on the project environment and project requirements. When the structure requires shotcrete with high early strength, sulfoaluminate cement or other early-strength cement may be selected, which generates relatively high heat, thus requiring certain preventive measures during use; when shotcrete is used for fire-resistant or acid-resistant structures, high-alumina cement should be selected; when shotcrete is used in areas with high soluble sulfate content, sulfate-resistant cement should be selected; when alkali reactions may occur between aggregates and water, low-alkali cement should be used. It is particularly emphasized that when selecting the type of cement, attention is to be paid to its compatibility with the accelerator. Improper selection of cement type may not only cause undesirable phenomena such as flash setting or delayed setting, excessively long initial and final setting times, but may also increase rebound, affect the strength development of shotcrete, and even lead to project failure.

Fine aggregate: apparent density of the fine aggregate ≥2500 kg/m^3, water absorption ≤3.5%, for shotcrete requiring frost resistance, the mass loss of the fine aggregate in freeze-thaw testing ≤10%, clay lumps ≤1.0, chloride ion content ≤0.02;

coarse aggregate: apparent density of the coarse aggregate ≥2500 kg/m^3, water absorption ≤3.5%, for shotcrete requiring frost resistance, the mass loss of the coarse aggregate in freeze-thaw testing ≤12%, clay lumps ≤0.25; the use of coarse aggregates with unstable chemical and physical properties is strictly prohibited;

limestone micro-powder: harmful clay content ≤1.2 g/100 g, $CaCO_3$ content ≥95%, CaO ≥53.2%, specific surface area ≥3000 cm^2/g; the chemical composition and physical properties of limestone are shown in Table 1 as follows:

Table 1



Chemical Composition (%)					Physical Properties
SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Apparent Density (g/cm²)
2.5	0.60	0.36	54.03	0.54	2.73
Tio2	SO3	K2O	Na2O	Loss on Ignition	Water Demand Ratio (%)
0.05	0.01	0.096	0.084	41.59	92

silica fume: moisture content ≤3%;

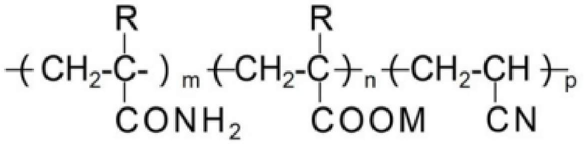
other admixtures: including slag micro-particles, activated clay, volcanic ash micro-powder, and ettringite-based synthetic admixture, etc.;

accelerator: including methyl sulfoxide-modified sepiolite and aluminum salt, obtained with modified polyhydroxy-alkylamine added and reacted in a reaction kettle for 3 hours; this preparation method increases the content of cohesive active substances, accelerates cement hydration, forms a large amount of ettringite, improves the cohesiveness of shotcrete mixtures, reduces shotcrete rebound rate, enhances concrete impermeability, and compensates for the loss of later compressive strength. The environmentally friendly high-strength alkali-free liquid accelerator is neutral or slightly acidic, with an alkali content of less than 0.1%, reducing the degree of damage to concrete; shotcrete incorporating this environmentally friendly high-strength alkali-free liquid accelerator exhibits higher density, with 1-day strength of mortar specimens reaching up to 14.5 MPa, 28-day compressive strength ratio as high as 95%, and excellent overall performance.

Nano spray rebound-reducing agent for concrete: prepared by polymerizing acrylamide, acrylic acid, and acrylonitrile monomers in an aqueous solution in the presence of a water-soluble free radical initiator, with a reaction temperature of 30-70°C for 2-7 hours, followed by neutralization and hydrolysis reactions at 50-70°C to obtain an acrylamide-acrylate-acrylonitrile terpolymer with a viscosity of 0.60-7.00 Pa·s for a 5 wt.% aqueous solution at 25°C. It is used in dry-mix, semi-dry-mix, and wet-mix shotcrete processes as well as a bonding enhancer for interior and exterior wall plastering of buildings. It demonstrates outstanding comprehensive performance characteristics including low dosage requirement, minimal rebound rate, reduced dust concentration, and excellent concrete strength development at all curing ages.

Mechanism of Nano Spray Rebound-Reducing Agent for Concrete:

The nano spray rebound-reducing agent for concrete employs a novel water-soluble polymer, namely an acrylamide-acrylate-acrylonitrile terpolymer, represented by the following formula:



$$\left(CH_2-\underset{CONH_2}{\overset{R}{C}}- \right)_m \left(CH_2-\underset{COOM}{\overset{R}{C}} \right)_n \left(CH_2-\underset{CN}{CH} \right)_p$$

where R represents H, CH_2 groups, and M represents Na, K, or other alkali metal ions, with m, n, p being positive integers.

The side chains of this terpolymer carry three different groups, each playing a distinct role when added to fresh concrete: the polymer chain side carries a certain density of anionic groups ($-COO^-$), while the surfaces of cement particles carry positive charges when cement is initially mixed with water, causing mutual attraction and accelerating cement particle flocculation. The $-CONH_2$ groups on the polymer chain side are hydrophilic groups distributed on the outer layer of cement particles, providing water-retaining and wetting effects, forming a flocculated structure that prevents cement particle dispersion. However, this flocculated structure may encapsulate excessive water, hindering water diffusion in fresh concrete and interfering with normal cement hydration. Tests prove that copolymers containing only the above two groups, while capable of reducing dust concentration and rebound rate, significantly decrease concrete strength at all ages. Therefore, a certain amount of hydrophobic -CN groups are introduced into this copolymer to moderately disrupt the flocculated structure formed by $-CONH_2$ groups, allowing unimpeded water molecule diffusion and normal cement hydration, thus maintaining concrete strength at all ages. By adjusting the ratio of these three groups (m : n : p = 70-80:15-20:5-10), the rebound-reducing admixture for shotcrete achieves excellent comprehensive effects. Depending on cement type, concrete mix proportions, and other factors, this ratio may be adjusted within a wider range. Additionally, the molecular weight of the copolymer plays a crucial role in the effectiveness of the rebound-reducing admixture for shotcrete. Higher molecular weight improves viscosity-enhancing effects but slows dissolution and diffusion in fresh concrete, making it difficult to fully function during spraying; lower molecular weight enables faster dissolution and diffusion but provides poorer viscosity enhancement. Therefore, selecting an appropriate molecular weight is one of the key factors for achieving high efficiency of concrete viscosity-enhancing agents. At 25°C, the viscosity of a 5 wt.% aqueous solution of this copolymer ranges from 0.60 to 7.00 Pa·s, preferably between 0.90 and 3.60 Pa·s.

Preferably, in step S2, the compactness of shotcrete is determined based on the comprehensive environmental grade, followed by selecting the binder formula according to compactness indicators; the strength grade of shotcrete is determined based on the surrounding rock grade, followed by selecting the concrete mix proportion according to the strength grade.

Calculation of Shotcrete Design Strength:

$f_{cu,0} \geq (f_{cu,k}+1 .645\sigma)\ k_1k_2$

where $f_{cu,0}$ is design strength of shotcrete (MPa);

$f_{cu,k}$ is standard value of concrete cubic compressive strength (MPa), taken as the design strength grade value of shotcrete;

σ is standard deviation of concrete strength (MPa), determined according to JGJ 55;

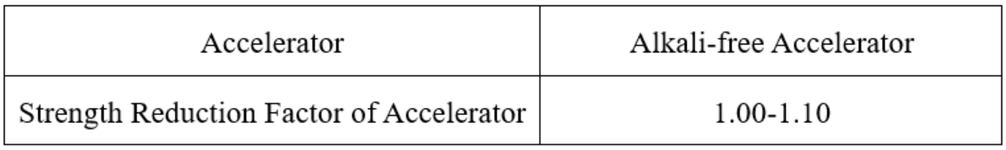
k_1 is reduction factor for compactness of sprayed concrete, refer to Table 2 for value ranges;

k_2 is strength reduction factor due to accelerator, refer to Table 3 for value ranges;

Table 2: Reduction Factor k1 for Compactness of Sprayed Concrete

Spraying Process	Wet-mix Spraying Process
Reduction Factor for Compactness of Sprayed Concrete	1.00-1.25

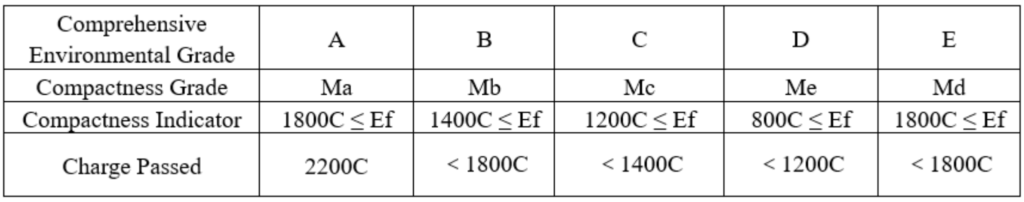
Table 3: Strength Reduction Factor k2 Due to Accelerator



Accelerator	Alkali-free Accelerator
Strength Reduction Factor of Accelerator	1.00-1.10

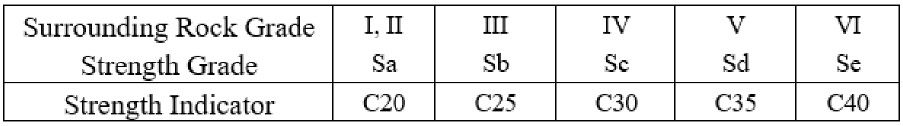
Based on the hazard level of environmental effects on tunnel structures, the comprehensive environmental grades are classified into five levels (A, B, C, D, E), where Grade E represents the most severe environment and Grade A the mildest. The relationship between the comprehensive environmental grade of tunnels and the compactness grades and compactness indicators of shotcrete are shown in Table 4. The relationship between surrounding rock grades and the strength grades and strength indicators of shotcrete is given in Table 5.

Table 4: Relationship Between Comprehensive Environmental Grade and Shotcrete Compactness Indicators



Comprehensive Environmental Grade	A	B	C	D	E
Compactness Grade	Ma	Mb	Mc	Me	Md
Compactness Indicator	1800C ≤ Ef	1400C ≤ Ef	1200C ≤ Ef	800C ≤ Ef	1800C ≤ Ef
Charge Passed	2200C	< 1800C	< 1400C	< 1200C	< 1800C

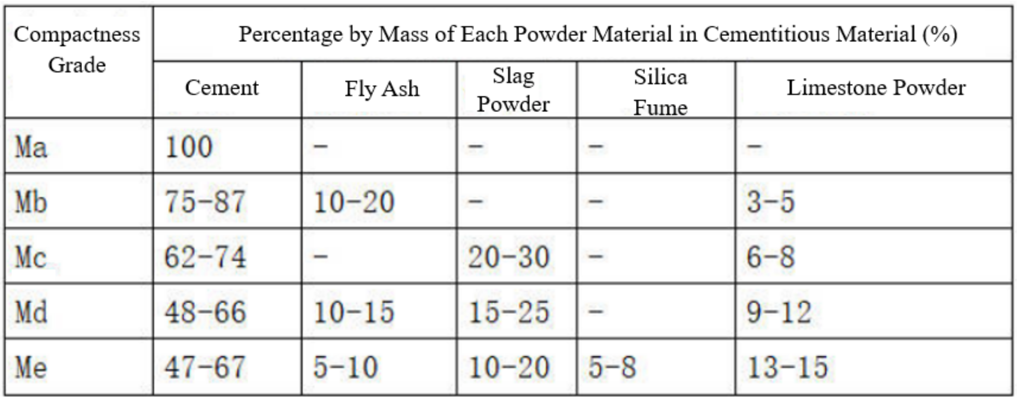
Table 5: Relationship Between Surrounding Rock Grade and Shotcrete Strength Indicators



Surrounding Rock Grade	I, II	III	IV	V	VI
Strength Grade	Sa	Sb	Sc	Sd	Se
Strength Indicator	C20	C25	C30	C35	C40

The design parameters for tunnel lining concrete are determined based on the comprehensive environmental grade and surrounding rock grade. The types and dosages of mineral admixtures incorporated into the cementitious material of the lining concrete are specified according to different compactness indicators. For the composite cementitious material, the formulations of the cementitious material for shotcrete determined according to different compactness indicators are shown in Table 6.

Table 6: Formulations of Cementitious Material for Shotcrete Corresponding to Different Compactness Indicators

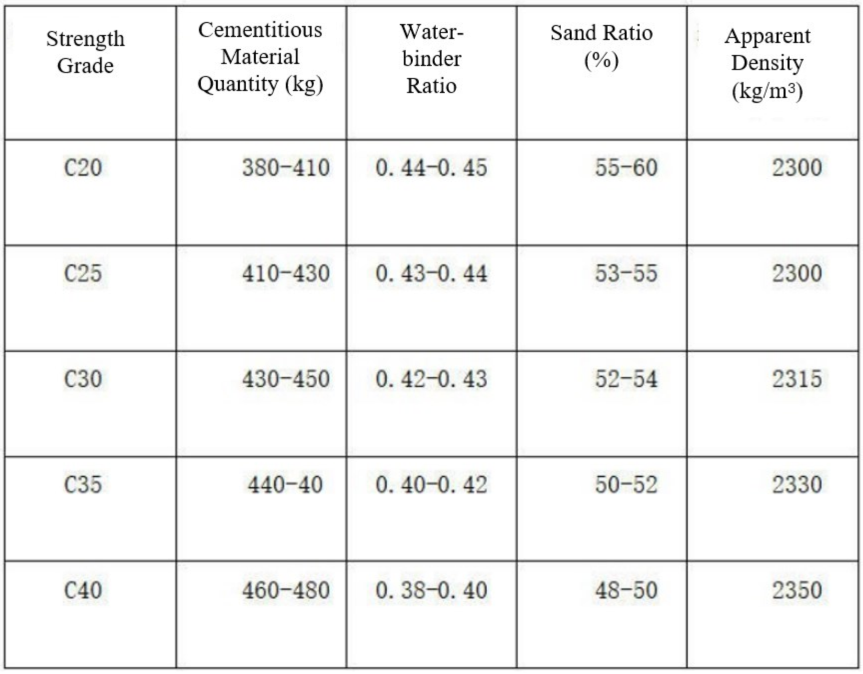


Compactness Grade	Percentage by Mass of Each Powder Material in Cementitious Material (%)				
	Cement	Fly Ash	Slag Powder	Silica Fume	Limestone Powder
Ma	100	–	–	–	–
Mb	75-87	10-20	–	–	3-5
Mc	62-74	–	20-30	–	6-8
Md	48-66	10-15	15-25	–	9-12
Me	47-67	5-10	10-20	5-8	13-15

The requirements for each powder material in the cementitious material are as follows. Cement: Ordinary Portland cement of grade 42.5, with a specific surface area >500 kg/m^2; fly ash: Grade I fly ash, with a specific surface area of about 750 kg/m^2; slag powder: Grade S105 slag powder, with a specific surface area ≥500 kg/m^2; silica fume: with a specific surface area ≥20,000 kg/m^2; limestone powder: with a specific surface area ≥600 kg/m^2.

Based on different strength indicators, the obtained cementitious materials for shotcrete are used as the main raw materials. After adding and mixing coarse and fine aggregates, the target series of concrete is obtained. The mix proportions are shown in Table 7.

Table 7: Shotcrete Mix Proportions Corresponding to Different Strength Indicators



Strength Grade	Cementitious Material Quantity (kg)	Water-binder Ratio	Sand Ratio (%)	Apparent Density (kg/m^3)
C20	380-410	0. 44-0. 45	55-60	2300
C25	410-430	0. 43-0. 44	53-55	2300
C30	430-450	0. 42-0. 43	52-54	2315
C35	440-40	0. 40-0. 42	50-52	2330
C40	460-480	0. 38-0. 40	48-50	2350

For tunnels in freeze-thaw environments, the cementitious material quantity adopts the upper limit value, and the water-to-binder ratio adopts the lower limit value; meanwhile, it is ensured that the water reducer and accelerator have excellent compatibility with the cementitious materials; for tunnels in freeze-thaw environments with developed groundwater, when composite cementitious materials are used for shotcrete, air-entraining water reducers is selected.

The dosage of silica fume is preferably 5% of the cementitious material quantity. The appropriate sand ratio for high-performance shotcrete is determined through testing. The standard for maximum size of coarse aggregate is to be taken as 10-15mm. Limestone micro-powder replaces a portion of fine aggregate, with a replacement rate of 15%.

When the wet-mix spraying process is adopted, the slump before entering the spraying machine is preferably (160±30) mm. The air content of high-performance shotcrete, especially in situations requiring freeze-thaw resistance, is to be 3-6% as the standard; in other situations, it may not be considered. For the selected concrete mix proportion, trial spraying tests are conducted and samples taken for performance testing. Based on its spray-ability performance, strength performance, and durability performance, the mix proportion is to be optimized and adjusted, and the shotcrete mix proportion is to be determined.

Preferably, in step S3, the prepared cementitious material, sand, and 1/3 of the water are put into the mixer for pre-mixing for 30 s; then the water reducer is added to the remaining water, mixed uniformly, and the mixture combined with all coarse aggregate is put into the mixer for mixing for 90 s.

When spraying the concrete, a plurality of transport vehicles alternately deliver materials to ensure sufficient supply of wet-mix shotcrete. In the transportation process, phenomena such as segregation of concrete, loss of cement paste, changes in slump, occurrence of initial setting are prevented.

Preferably, in step S5, the rock surface to be sprayed is treated before spraying. The loose dust and rock chips on the rock surface to be sprayed are washed away with high-pressure water. When the rock surface is deliquesced or argillized by water, the rock surface is cleaned with high-pressure air. For muddy or sandy rock surfaces, a fine steel mesh is installed. It is fixed with circumferential rebar, anchor nails, or directly onto the steel frame to ensure close contact with the surface to be sprayed for improved shotcrete adhesion. Before the concrete is sprayed, a layer of cement mortar is first sprayed, and then the concrete is sprayed after the final setting.

When there is water inflow on the spraying surface, not only does the adhesion of shotcrete deteriorate, but the shotcrete may also be washed away or spalled, resulting in reduced work efficiency. Therefore, it is necessary to perform appropriate water inflow treatment before shotcrete construction. The water inflow treatment is preferably conducted at localized water inflow points. In cases with water inflow, the adhesion of shotcrete is reduced, leading to loss of shotcrete and increased water pressure behind the hardened layer, which are major causes of quality degradation, cracking, and delamination of shotcrete. For this reason, in cases with water inflow, drainage pipes and filtration materials are installed to perform drainage treatment. Additionally, during construction near tunnel portals in cold regions, care must be taken to prevent the spraying surface from freezing.

The excavated wall surface may contain loose rocks, adhered clay, and drilling dust. If not treated before shotcrete construction, proper bonding with the surrounding rock cannot be guaranteed, and voids may form between the shotcrete and the surrounding rock, preventing full functionality of the support. Therefore, before spraying, compressed air and water are used to wash away clay, loose rocks, and other debris. To ensure safety during shotcrete construction and achieve integral bonding between shotcrete and surrounding rock, potentially unstable loose rocks are removed in advance.

The excavated wall surface and the shotcrete surface should be smooth, avoiding extreme unevenness to minimize shotcrete consumption. Excessive surface irregularities increase rebound. Smooth blasting is effective in achieving even wall surfaces. The use of computer-controlled drilling jumbos to control overbreak of the wall surface also proves beneficial. In cases where the shotcrete surface exhibits severe unevenness, voids are likely to form behind the secondary lining, compromising lining thickness and potentially causing cracks. Therefore, the shotcrete surface is finished to achieve smoothness.

Preferably, in step S6, markers are set to control shotcrete thickness by embedding rebar heads as indicators and inserting iron wires 5 cm longer than the design thickness at 1-1.5 m intervals in spraying for construction control.

When the surface to be sprayed encounters water inflow, seepage, or damp rock conditions, treatment according to different situations must be performed before shotcrete construction.

(1) Large water inflows are treated by grouting for water sealing before shotcrete is applied.

(2) Small water flows or fissure seepage are treated by either rock surface grouting or pipe drainage before shotcrete is applied.

(3) Large-area damp rock surfaces are treated with highly adhesive concrete, such as by adding additives and admixtures to improve concrete performance.

Machinery, equipment, and pipelines for air, water, and electricity are inspected. An Aliva wet-mix shotcrete machine unit is used for the concrete spraying construction. The wet-mix shotcrete machine is positioned and trial operation is conducted. The spraying volume is adjusted via a handwheel after the wet-mix shotcrete machine motor is started, with real-time adjustments in spraying based on air volume and spraying requirements displayed on the screen menu. For the liquid accelerator, the mix proportion menu is entered and the accelerator addition amount is set at 2% of the cement dosage per cubic meter of concrete. In the construction process of shotcrete, premixed concrete is mixed with the accelerator near the nozzle and then instantly sprayed onto the base layer, with the mixing and spraying process lasting less than 1 minute. However, the existing standards and specifications stipulate that the initial setting time of accelerators should be less than 5 minutes, resulting in a significant time gap. This leads to the shotcrete remaining in a plastic state during construction, making it fundamentally impossible to achieve sufficient bonding strength with the base layer, which is the root cause of high rebound rates.

The adoption of the Aliva wet-mix shotcrete machine unit overcomes major deficiencies such as material waste and low operational efficiency caused by operator response delays in MEYCO and other types of shotcrete manipulators. Compared to manual wet-mix spraying processes, the manipulator provides a larger spraying range, higher spraying pressure, better angle maintenance, and eliminates the need for scaffolding work platforms. Essentially, a single operator may complete the spraying operation, and the quality is significantly superior to manual spraying.

The selected air compressor must meet the working air pressure and air consumption requirements of the shotcrete machine. Compressed air must undergo oil-water separation before entering the shotcrete machine. The material delivery hose should withstand pressures above 0.8 MPa and possess excellent wear resistance. Good ventilation and lighting conditions are ensured in the work area. The ambient temperature during spraying operations is not lower than 5°C.

After tunnel excavation is completed, a 4 cm thick layer of concrete is first sprayed to seal the rock surface. Rock bolts are then installed, steel frames are erected, and reinforcing mesh is hung. After cleaning the initially sprayed rock surface, a subsequent spray is applied to reach the design thickness.

Preferably, in step S6, the spraying sequence is to spray the wall first and then the arch, from bottom to top, moving in an S-curve; spraying is started from the bottom of the sidewalls on both sides of the tunnel and closed at the centerline of the arch crown to complete a trial spraying of a ring of shotcrete.

The nozzle is kept perpendicular to the surface in spraying; when spraying perpendicular to the rock surface, the continuous “thin flow” of concrete has a secondary embedding effect on the rebound materials, reducing rebound rate and increasing single-layer thickness.

A distance between the nozzle and the rock surface is maintained of 1-1.5 m.

Shotcrete rebound is greatest during initial spraying, becomes minimal and stabilizes when the rock surface coverage reaches 2-3 cm in thickness; when the sprayed concrete adhering to the rock surface begins sliding or flowing, the maximum single-layer thickness is achieved, at which point spraying must not continue, and re-spraying may only be performed after the initially sprayed concrete has reached its initial setting stage.

Preferably, in step S6, first, the boom of the manipulator is extended to adjust the spraying position of the nozzle at the bottom of the sidewall. The automatic parallel function of the forearm of the manipulator is used to adjust the forearm to be horizontal to the ground and parallel to the sidewall of the tunnel. Then, the nozzle distance and angle are adjusted. After the above work is completed, spraying is commenced without further adjustments to the nozzle distance, angle, or the boom of the manipulator during spraying. Only the automatic extension function is used to control the nozzle to automatically extend and retract on the forearm, that is, it is slowly moved from one end to the other end and back 2-3 times to complete one spraying. Then, the boom is extended by 30 cm. The boom is moved vertically and horizontally to ensure the angle and distance between the nozzle and the rock surface, and the next part is sprayed in the above-mentioned sequence. This cycle is repeated to complete the spraying of the surface to be concreted.

When pipeline blockage occurs in the spraying process, the Aliva shotcrete machine and metering pump are immediately shut down, the delivery pump is turned off, the hose is tapped, and the residual concrete in the pipeline is discarded. After completing the blockage treatment, water is first sprayed to flush the pipeline, and spraying operations may only be resumed after ensuring the pipeline is completely unobstructed.

In the spraying process, the addition of water to the concrete mixture is strictly prohibited. If concrete consistency adjustment is required, the site technician is promptly notified for appropriate handling. For areas with overbreak, water seepage, or structurally complex conditions, the accelerator dosage is increased in advance in spraying, and the number of spraying passes is enhanced, as this adversely affects normal cement hydration. Upon completion of each work shift, the pumping pipeline of the wet-mix shotcrete rig and the accelerator delivery pipeline are thoroughly cleaned to ensure unimpeded flow. For accelerator storage, the specifications are strictly followed, including covering for thermal insulation and implementing freeze-proofing and sun-shading measures.

Preferably, in step S7, spray-based curing is adopted for rock tunnels and liquid curing agents for loess tunnels, with a curing duration ≥14 days; water curing is prohibited when temperatures are below +5°C.

The thickness inspection of shotcrete is in principle conducted using the inspection hole method. The inspection interval is set at every 20 meters for one cross-section; with at least 5 measurement points in the vault section and 1 point each on both left and right sidewalls. The inspection methods may adopt either the inspection hole method or the inspection nail method.

Preferably, in step S9, 3D laser scanning is employed for detection. High-precision station information and 3D models of the working face pre -/post-spraying are acquired via 3D laser scanning technology combined with multi-modal fusion station technology. The positions of the solid models in two time dimensions are aligned in the same spatial system. Projections are converted to obtain high-density 2D cross-sections. The formed volume of the shotcrete is calculated via 2D section comparison to derive rebound volume from total sprayed volume.

3D laser scanning for tunnel profile measurement includes the following methods.

Establishment of reference points: the reference points for profile measurement adopts the same coordinate datum as construction layout, serving as positioning references for 3D point clouds within the engineering coordinate system. A pair of reference points are established every 10 meters within the profile measurement area, with densified measurements conducted under the framework of the underground construction control network.

The reference point markers are preferably made of stainless steel, with a 0.5 mm deep cross engraved at the center. The top surface of the markers is positioned at least 5 cm below the driving surface to prevent the pile core from being crushed and damaged by mechanical equipment. Reference points are established at stable, reliable, and undamaged positions that are convenient for measurement, and measures are taken to prevent settlement and resist displacement. Control point markings are clear, complete, and easily identifiable.

To ensure the reliability of reference point results, the following verification measures are implemented during reference point measurement.

After setting up the total station via the underground construction control network, the three-dimensional coordinates of a third point are verified and recorded. If the discrepancy falls within the allowable tolerance, it confirms that no errors occurred during station setup, including the use of control points and results, instrument target placement, and orientation settings. Subsequent measurements may then proceed. The prism holder is centered and leveled on the reference point pile core. The point number and prism height are jointly confirmed by the foresight and instrument operator before measurement and data recording. After completing measurements of the all the measuring points at a single station, the placement status of the instrument is inspected. If no errors are found, other control point results are rechecked and recorded. If the measured discrepancies of verification points remain within allowable limits, the instrument is deemed stable and reliable throughout the surveying process, and the measurement results are considered valid. Upon completion of measurements, the reviewing personnel retrace the reference point measurement process step by step from the data cited during station setup to the check of the control point results at the end of the measurement. According to the original records, the possibility of errors in each link is excluded to ensure the reliability of the measurement results.

Fixed measuring point orientation: the centering and orientation function provided by the total station scanner is utilized. The total station scanner is set up on a known measuring point to complete precise centering and leveling. The known coordinates of the station and the backsight control point are input into the system. After aiming at the backsight control point, the station orientation of the total station scanner is completed.

Point cloud acquisition: the 3D point cloud data of the tunnel profile is rapidly and comprehensively acquired at the construction site, mainly relying on the increasingly mature 3D laser scanning technology. The 3D laser scanning technology is a method of high-speed laser scanning measurement, which may quickly obtain the 3D coordinate data of the surface of the measured object over a large area and with high resolution. It may rapidly and massively collect spatial point information, providing a brand-new technical means for quickly establishing a 3D image model of an object. It has the characteristics of rapidity, non-contact, real-time, dynamic, initiative, high density, high precision, digitalization, and automation.

Currently, common three-dimensional laser scanners used at tunnel construction sites include brands such as Z+F, FARO, Leica, and Trimble. Mainstream scanners may meet the indicators such as a scanning speed of about 1 million points per second, a ranging accuracy of 2 mm/25 m, a resolution of 3.5 mm/25 m, and a measuring range of more than 70 m. They may complete the scanning of a 40-meter tunnel section within 5 minutes.

Precautions for field operations of 3D laser scanners are as follows.

To avoid the obstruction of structures, the point cloud within a 20-meter range in front of and behind the instrument at each scanning station is taken as valid data. The positions of the spherical targets are simultaneously acquired by the scanner during the scanning of the tunnel profile, and no less than two spherical targets are used at each station. A Leica spherical prism is used in conjunction with a support and placed on the reference point. The height of the prism is read, and the spherical surface faces the scanner. To ensure the acquisition accuracy of the spherical targets, the distance between the spherical targets and the scanner is preferably 5-10 meters. The basic name of the scanner station is generally set as representative characters such as “Z” (left line) and “Y” (right line), followed by a serial number, such as “Z001”. Before starting the measurement, the scanner is pre-heated, and after the pre-heating is completed, the normal operation of all connections is tested. After starting the 3D laser scanning, the operators should avoid the effective scanning area. After the operation of the 3D laser scanner is completed, the data is automatically stored, and the instrument is moved to a new station. The distance between stations does not exceed 40 meters, and pre-heating is not required after moving the station.

Multi-modal fusion station setup: the positioning of 3D point cloud data is the key to the accuracy of 3D data. The center of the spherical prism is fitted according to the scanned point cloud data of the spherical surface of the spherical target, the position of the control point is determined, and then it participates in the station adjustment. Finally, the 3D point cloud of this station is positioned in the engineering coordinate system, obtaining the absolute position of the point cloud and avoiding the systematic introduction errors caused by the overlapping method of conventional scanners. In the existing applications of 3D laser scanning technology, due to the interference of the surrounding point cloud data on the point cloud data of the spherical surface of the spherical target, it often causes difficulties in fitting the center of the target and the inability to meet the accuracy requirements. In the target fitting process, the point cloud around the target is hidden through an algorithm to reduce the interference of target fitting, thereby improving the accuracy and efficiency of target fitting. After importing the point cloud data into the processing software, the center of the spherical prism is fitted according to the point cloud data of the spherical surface of the spherical target. The closer the spherical target is and the better the visibility conditions are, the higher the fitting accuracy will be. More than two successfully fitted reference point data at each station are required to participate in the intersection adjustment of the angular and side observations. The successfully fitted reference point data and the height of the spherical target used during scanning are input into the software, and combined with the results of fixed measuring point orientation and angular and side intersection adjustment, the weighted adjustment of multi-source observations is carried out to obtain high-precision station setup results and three-dimensional point cloud data in the construction coordinate system.

Projection conversion to high-density two-dimensional sections: after the point cloud data is imported into the post-processing software, a 360-degree original image may be generated. The original image data is backed up, and the data is processed in sequence.

Calculation of the formed volume by the section method: after processing the point cloud data such as noise filtering and orthographic projection, the solid models before and after shotcrete construction are analyzed together. Based on the central axis of the construction line, high-density two-dimensional transverse section maps with a minimum interval of 2 cm are extracted and generated. The area between the two measured contours in each two-dimensional section is calculated in batches. The average value of the areas of adjacent sections is multiplied by the interval distance and accumulated to obtain the volume of the formed shotcrete in a certain section.

Analysis and statistics of the rebound volume: after subtracting a certain amount of equipment loss from the total amount of shotcrete in the same section, the proportion of the formed concrete can be obtained by comparing it with the formed volume. The remaining volume is the rebound rate of the shotcrete.

Only the preferred examples of the present invention have been described in detail above. However, the present invention is not limited to the above-mentioned examples. Within the scope of knowledge of those of ordinary skill in the art, various changes can be made without departing from the purpose of the present invention, and all such changes are included in the protection scope of the present invention.