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ANALYSIS ON THE INFLUENCE FACTOR OF LOW-STRENGTH WET SHOTCRETE IN FRIGID MINING AREA

Wet shotcrete technology is being gradually used in roadway support in frigid mining areas. Thus, problems such as low strength, fragility, and high repair rate have also emerged. This study focuses on low strength, cracking, and other problems in the wet shotcrete support of a mine. It introduced the fishbone diagram to investigate the effects of temperature, cement content, and water-cement ratio (W/C) on the strength of the shotcrete layer. The microscopic morphology of wet shotcrete based on scanning electron microscopy (SEM) is observed. Results demonstrated that temperature was the main influencing factor of wet shotcrete in frigid mining areas. When the curing temperature was lower than 10°C, the early strength of wet shotcrete dropped significantly. Temperatures above 15°C were favorable for later gain in strength. W/C was of a complementary relationship with strength development at different ages. Temperature was the essential factor that influenced the microscopic morphology of wet shotcrete. Furthermore, internal initial porosity and aggregate interface bonding strength had a direct effect on macro-mechanical properties of wet shotcrete.

Keywords: Wet shotcrete; Frigid area; Fish-bone diagram; Temperature; Low strength

1. Introduction

Wet shotcrete is a type of shotcrete. Kall Akeley began using shotcrete technology in 1907 (Rispin et al., 1999). In recent years, wet shotcrete technology has been gradually promoted in large-section underground engineering, such as hydropower, because of its high production efficiency and excellent engineering quality. However, its application in underground mines in

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China is still at its infancy. The use of dry shotcrete machine in underground coal mines in China has been forbidden since January 27, 2012. Thus, wet shotcrete technology has been an inevitable choice for mine underground shotcrete. With the large-scale mining of mineral resources, an increasing number of mining resources in the frigid area have been exploited. Altitudes of these area are between 1,500 m and 5,000 m, with daily average temperature of ≤10° throughout the year. The total area of high latitude area in China is 2.891 million km^2, whose regional resource reserves account for above 50% of the total resources reserves in China (Zhao et al., 2013). The wet shotcrete support technology will be gradually involved in the roadway support of mines in frigid areas. Low-temperature environment brings a great challenge to the application of wet shotcrete technology. Low temperature seriously affects properties, such as condensation and rheology, especially the strength of wet shotcrete.

Mechanics and rheological properties of wet shotcrete have been the emphasis and interest of research in current studies of wet shotcrete technology (Yun et al., 2015; Wang et al., 2015, 2016). Han et al. (2010) applied wet shotcrete technology to the roadway support of fractured rock mass in Jinfeng gold mine. The results showed that the strength of wet shotcrete could be improved by 45%-85% compared with that of dry shotcrete under the same condition. Wang et al. (2010) studied the shotcrete support mechanism of underground broken roadway. They indicated that annual roadway collapse amount could be lowered to 77% by adopting wet shotcrete technology. Malmgren et al. (2005) investigated cracking and shrinkage problems of wet shotcrete and indicated that shrinkage cracks were generated in the interface between shotcrete and rocks. These studies focused on wet shotcrete under room temperature. However, few works have been conducted on the shotcrete support technology in frigid mining areas. The most remarkable characteristic of frigid areas is low temperature. Temperature exerts an important influence on the development of concrete strength. Thomas (1969) observed a considerable influence on concrete strength when the temperature was below 10°C. Husem et al. (2005) studied the compression strengths of concrete under curing conditions of 10°C, 5°C, 0°C, and −5°C, results of which showed that concrete strength decreased with temperature. Compression strengths at 10°C and −5°C were 14.9 MPa and 2.7 MPa, respectively, which could reach 21.4 MPa under a standard curing condition. Fall et al. (2009) and Pokharel et al. (2013) studied the strength of cement filling body under curing conditions of 2°C, 20°C, 35°C, and 50°C. The results showed that the strength of cement filling body increased linearly with the curing temperature. Qiao et al. (2016) studied the kinetic features of concrete under low temperatures of 28°C, 0°C, 15°C, and 30°C by adopting split Hopkinson pressure bar. The results showed that temperature had the greatest effect on the kinetic features of concrete. In terms of tunnel engineering, studies have also been conducted on failure and freeze-thawing mechanism of concrete lining in the frigid areas. Chen et al. (2014, 2015) studied the microstructure of shotcrete using computed tomography scan under freezing-thawing circumstance. The results indicated that the destruction of shotcrete microstructure increased with the amount of freeze thawing. When the freeze thawing reached 300 times, the loss of uniaxial compression strength (UCS) could reach 63.78%. Yang et al. (2004) successfully applied shotcrete technology in the temporary support of Kunlun tunnel in the Qinghai-Tibet railway by adopting a temperature-control measure to ensure that the temperature of mixing object would be no less than 10°C during spraying. Great distinctions between wet shotcrete support of mine and that of tunnel exist. With the wet shotcrete support of mine as a permanent support and the continuous and accumulative effects of loads, such as ground pressure and blasting, adopting a forced convection heater can improve its curing temperature in tunnel construction. Therefore, studying wet shotcrete support technology in frigid areas is of great significance, especially the influence of temperature on strength for roadway support in the frigid areas and mineral resource exploitation.

Therefore, fish-bone diagram was firstly adopted in this paper to identify influencing factors of shotcrete technology in the frigid areas to find out critical influencing factors under the background of low-strength spraying layer, partial cracking and falling phenomenon occurred in shotcrete roadway support of underground broken rocks in a mine. Secondly, it studied the influence rule of cement content and water-cement ratio (w/c) on the compression strength of wet shotcrete as well as analyzed the micro-structure of shotcrete under different working conditions. The optimal proportion and technology measures that suitable for shotcrete support of roadway in a mine were ultimately proposed through site experiments.

2. Project profile

2.1. Survey of the mining area

The mine is located between 3,000 and 4,000 meters above the Qinghai–Tibet plateau. The mine is in the temperate frigid zone, with annual average temperature of 4°C. The average temperature of the hottest month is approximately 10°C, whereas that of the coldest month is –8°C. The temperature variation of the mine in 2009 is presented in Fig. 1. Temperature has become a key factor that influences the support.

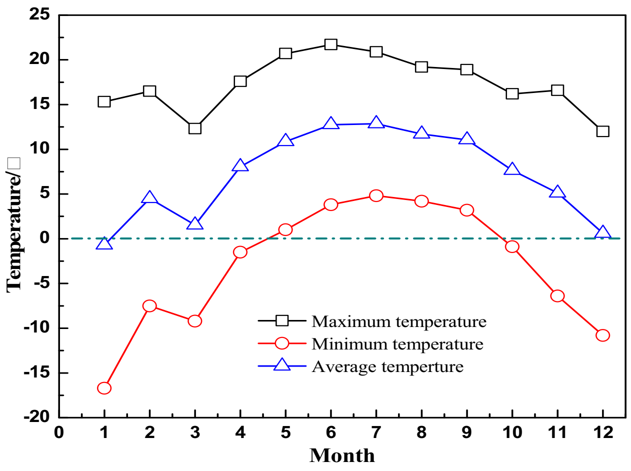


Fig. 1. Temperature variation of the mining area in 2009

2.2. Supporting technology for wet shotcrete

For the effective support of roadways, the mine is introduced with wet shotcrete technology. The strength grade of the shotcrete is C25, with supporting thickness of 100-200 mm. The technology can be mainly divided into surface preparation of wet spraying material, spraying material transportation, and underground spraying.

(1) Surface preparation of wet spraying material: Aggregate and fiber matched by a dosing machine in a proper proportion are delivered to a teeter chamber through a belt. Cement is added through a cement bin. A JZC1000 mixer is used to mix the spraying materials. Cement weighing, water weighing, admixture weighing, electrical, and air circuit systems are also used. Workers control the batching in a control room outside of the mixing station.

(2) Transportation of wet spraying material: Wet spraying slurry prepared on the surface should be transported to the underground wet shotcrete work surface on the premise of stability conservation. A Mixtec UV2-HD(4 m^3) shotcrete tank car that is suitable for underground working is adopted in the mine for transportation. The tail of the tank car can be lifted to facilitate concrete slurry to pour into the hopper of a shotcrete trolley. Concrete tank is revolved continuously during transportation for mixing concrete. In this manner, concrete can maintain a good rheological property without precipitation and separation during transportation.

(3) Underground construction of wet shotcrete construction: MEYCO Cobra concrete-spraying trolley is used in the mine for wet spraying support. The remote-controlled mechanical arm is adopted in spraying concrete. The nozzle can be rotated 360° with a maximum volume of 20 m^3/h. During concrete spraying, the accelerating agent is delivered to the nozzle by an accelerator pump for evenly mixing with concrete.

2.3. Existing problems of wet shotcrete support

Many problems have been experienced in the application processes of wet shotcrete technology, especially in mixing, curing, and strength of concrete under frigid temperatures, because the mine is located in a frigid and high-altitude area. The situation may also lead to phenomena, such as wet shotcrete failing to reach the designed strength, spraying layer drop off, and cracks occurring in the support roadway. Therefore, studying the influencing factors of wet shotcrete support at low temperatures in a mine has been of great importance to the application of wet shotcrete technology in mines in frigid areas.

3. Analysis of wet shotcrete using low-strength fishbone diagram

Fishbone diagram is also called cause-and-effect or characteristic diagram. The method was first introduced by Japanese Ishikawa Kaoru in 1953 (Chan et al., 2002; Li et al., 2011). Fishbone diagram can fully analyze the cause of a problem. This study introduces the method to analyze the influencing factors of wet shotcrete in a mine. The influencing factors of strength of wet shotcrete failing to reach the requirements designed in frigid areas are analyzed from the aspect of personnel, machine, material, method, environment, and measurement. Final results are obtained by testing and eliminating assumptions one by one, as shown in Fig. 2.

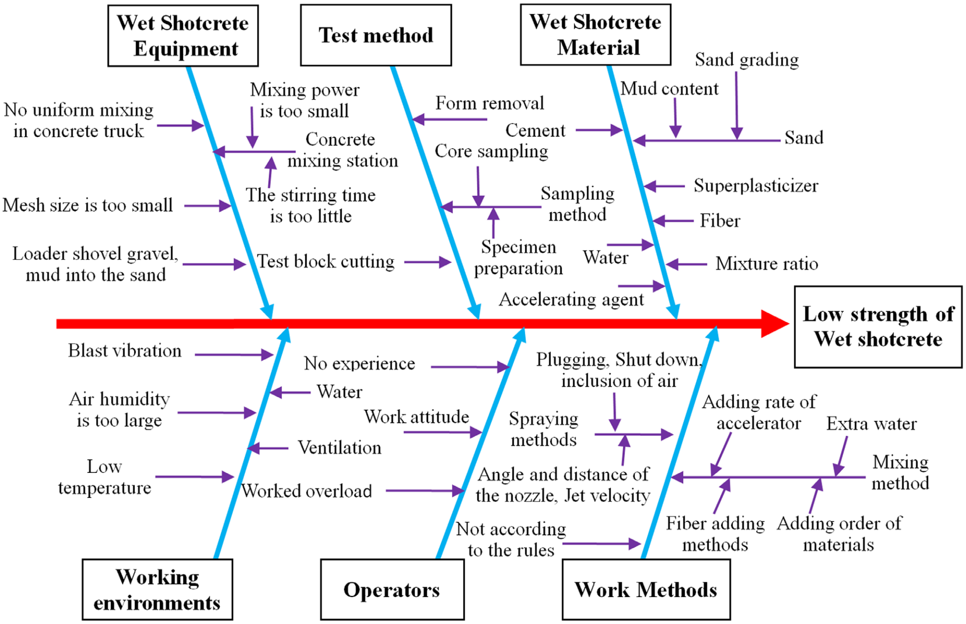


Fig. 2. Fishbone fig analysis of shotcrete low strength

Through analysis, the influencing factors of wet shotcrete support in the frigid mining area of a mine are mainly reflected in five aspects.

(1) Low temperature: The mine is at low temperatures all year long. The temperature of sand and gravel are between 0°C and 5°C. A low temperature can affect the chemical reaction rate of cement, water reducing agent, water and aggregate, as well as lower the fluidity of the mixture.

(2) Less mixing time: Effective mixture of wet spraying materials can increase the uniformity of slurry. The mixture contains excellent rheological properties. Intensive mixing can effectively break the reunion of cement particles, stimulate the activity of cement, and improve the strength of wet shotcrete. However, the activity of cement decreases at low temperature, which can only be improved through strong and effective mixing. Moreover, the slurry on site is not fully and evenly mixed.

(3) Excessive water-cement (W/C) ratio: Given the severe slurry reunion caused by low temperature and inefficient mixing time, workers on site have added a large amount of water, making the wet spraying materials to be mixed evenly in short time. The strength of wet shotcrete decreases with the increase of W/C ratio.

(4) High mud content in gravel: Wet shotcrete currently used in the mine has high mud content with low gravel strength. This condition introduces a large amount of particle materials, which decreases the shotcrete strength entirely.

(5) Unreasonable mixing ratio: The wet shotcrete mix proportion used currently is designed on the basis of a region with normal temperature (annual average temperature is higher than 15°C), which apparently does not conform to the actual situation of low-temperature environment in the mine.

Therefore, the fundamental influencing factor of low-strength shotcrete in the mine is low temperature, which results in inadequate mixing time, increases W/C ratio, slow cement hydration, failure of water reducing agent and accelerating agent. Such conditions lead to the unreasonable slurry ratio of the shotcrete.

4. Materials and experiments

4.1. Materials

On the basis of the analysis of the fishbone diagram, machine-made sand with few mud content (−10 mm) is selected as sand and gravel. The particle size distribution curve is shown in Fig. 3. The content of −5 mm particles in the sand is 80.5%, with only 5.6% of the −0.15 mm small particle content, 42.5 common Portland cement, steel fiber with imitation plastic at a length between 20 mm and 30 mm. The RHEOPLUS 26 water reducing agent and SA167 accelerating agent of BASF (Badische Anilin-und-Soda-Fabrik) are selected.

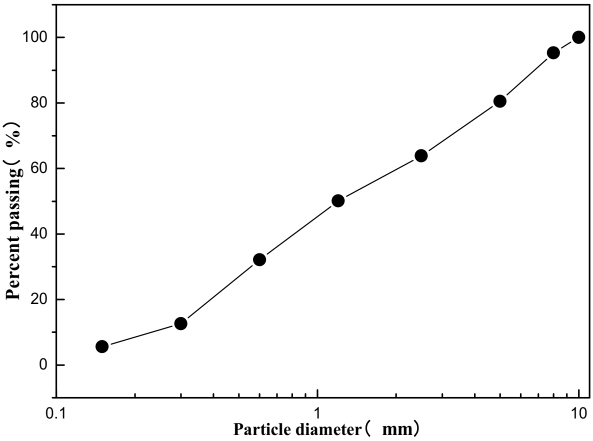


Fig. 3. Grading curves of aggregate

4.2. Experimental plan

Wet shotcrete mix proportion experiment was conducted at a low temperature to investigate the influence of curing temperature on the strength of wet shotcrete, considering the effect of W/C ratio, cement content, and water reducing agent on the working properties of the wet shotcrete. The wet shotcrete in the experiment was designed on the basis of C25 concrete with slumps between 15 cm and 20 cm. Curing temperatures in the experiment were 5°C, 10°C, 15°C, and 20°C with relative humidity of 80% RH. W/C ratios of wet shotcrete were 0.44, 0.46, 0.48, and 0.5, whereas the mixing amount of cement were 400, 415, 430, and 445 kg/m^3, respectively. UCS test should be conducted within the 7 and 28 days of curing period. The microstructure of concrete should also be observed at the same time.

4.3. Experimental method and process

Batching was conducted according to the mix proportion of web spraying material designed for the experiment. The mixer was adopted to mix the slurry evenly before pouring into trial mold of Φ80 mm × 200 mm. The slurry should be cured in the curing chamber upon demolding in 24 h. When conducting shotcrete industrial experiment, the shotcrete trolley was controlled to spray the slurry into the sampling mold (300 mm × 300 mm × 260 mm) on site. Its curing conditions were consistent with the previous one. Upon curing to preset age, the test blocks were delivered to the surface for cutting into standard blocks of Φ80 mm ×160 mm. Universal press was used to measure UCS of 7 and 28 days. Scanning electron microscopy (SEM) was used to observe the microstructure of concrete in a typical mix proportion.

5. Results and discussion

5.1. Influence of temperature on the strength of wet shotcrete

When the cement content of wet shotcrete concrete slurry was between 400 kg/m^3 and 445 kg/m^3 under a curing temperature of 5°C~20°C, UCS experiments of 7 and 28 days were conducted on the concrete test blocks. Table 1 shows the results.

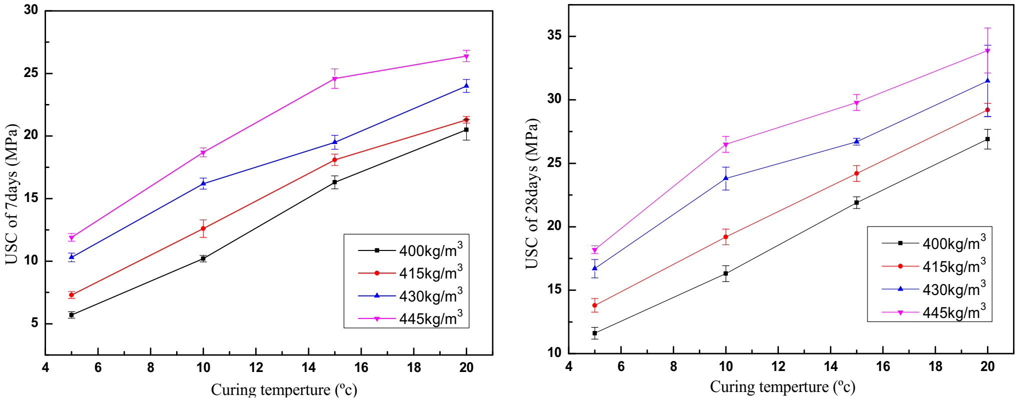
TABLE 1

Curing temperature on UCS of wet shotcrete (w/c:0.48)

Cement Kg/m^3	**Curing temperature**	**UCS/MPa**		**Curing temperature**	**UCS/MPa**	
		7d	**28d**		**7d**	**28d**
400	5°c	5.7	11.6	15°c	16.3	21.9
415		7.3	13.8		18.1	24.2
430		10.3	16.7		19.5	26.7
445		11.9	18.2		24.6	29.8
400	10°c	10.2	16.3	20°c	20.5	26.9
415		12.6	19.2		21.3	29.2
430		16.2	23.8		24.0	31.5
445		18.7	26.5		26.4	33.9

The results of the experiment indicated that under different cement content, 7 days and 28 days of UCS of wet shotcrete increased with the curing temperature. When the cement content was 400 kg/m^3, 7-day strength increased from 5.7 MPa at 5°C to 20.5 MPa at 20°C. As shown in Fig. 4, when the cement content was 400, 415, 430, and 415 kg/m^3 with curing temperature increasing from 5°C to 10°C, the 7-day UCS increased by 78.9%, 72.6%, 57.2%, and 57.1%, respectively, whereas that of the 28 days increased by 40.5%, 39.1%, 42.5%, and 45.6%, respectively. When the temperature increased from 10°C to 20°C, the 7-day UCS increased by 100.9%, 69.0%, 48.1%, and 41.2%, whereas that of the 28 days increased by 65.0%, 52.1%, 32.3%, and 52.1%, respectively. The 7-day UCS of shotcrete in the early stage was affected remarkably when the temperature is below 10°C. The influence of temperature on strength in the early stage relatively decreased with the increase of cement content (Fig. 4a). When the curing temperature is greater than 15°C (Fig. 4b), 28-day UCS of wet shotcrete increased significantly. Therefore, when the ambient temperature was lower than 10°C, the temperature had a significant influence on the strength in the early stage. When the ambient temperature was greater than 15°C, the temperature was conducive to increase the strength in the later stage.

Under the same curing temperature, 7- and 28-day UCS increased with the cement content. The influence of cement content on strength existed in critical intervals. When the content was larger than the critical interval, the strength of the shotcrete significantly increased. As shown in Fig. 4, when the cement content exceeded 415 kg/m^3, 7- and 28-day UCS of shotcrete increased considerably. At 5°C, 7-day UCS increased from 7.3 MPa with cement content of 415 kg/m^3 to 10.3 MPa with cement content of 430 kg/m^3; the 28-day UCS increased from 13.8 MPa with cement content of 415 kg/m^3 to 16.7 MPa with cement content of 430 kg/m^3.



(a) Uniaxial compression strength of 7 days (b) Uniaxial compression strength of 28 days

Fig. 4. Relationship curves between Curing temperature and UCS

The development of wet shotcrete strength was a compound result of curing temperature and cement content. The effect of temperature on the strength of wet shotcrete gradually decreased with the increase of cement content. Thus, the strength of wet shotcrete could be improved by indirectly adding the additive amount of cement. The strength design of wet shotcrete in the mine was C25 with a control of slumps between 15 cm and 20 cm. By considering actual situations on site, the cement content should be in the range of 420-440 kg/m^3.

5.2. Influence of W/C ratio on wet shotcrete strength

The W/C ratio affected the concrete hydration of shotcrete. Thus, changes in internal structure occurred. Table 2 presents the experimental results under the influence of W/C ratio and cement content on the experimental results of 7- and 28-day UCS under low temperature (10°C).

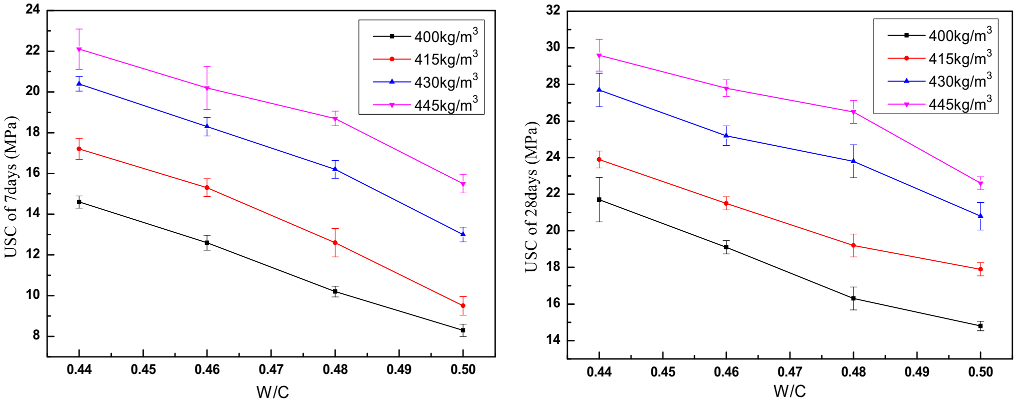
The experimental results indicated that under different cement contents, 7- and 28-day UCS of wet shotcrete decreased with the increase in W/C ratio. The compression strength under different ages increased with the cement content under the same W/C ratio. When the W/C ratio increased from 0.46 to 0.48, 7- and 28-day strengths of wet shotcrete changed significantly.

TABLE 2

W/C on the UCS of wet shotcrete (10°C)

Cement Kg/m^3	W/C	UCS/MPa		W/C	UCS/MPa	
		7d	28d		7d	28d
400	0.44	14.6	21.7	0.48	10.2	16.3
415		17.2	23.9		12.6	19.2
430		20.4	27.7		16.2	23.8
445		22.1	29.6		18.7	26.5
400	0.46	12.6	19.1	0.50	8.3	14.8
415		15.3	21.5		9.5	17.9
430		18.3	25.2		13.0	20.8
445		20.2	27.8		15.5	22.6

As shown in Fig. 5, interval also existed in the influence of W/C ratio on strength. The critical interval was between 0.46 and 0.48.



(a) Uniaxial compressive strength of 7 days (b) Uniaxial compressive strength of 28 days

Fig. 5. Relationship curves between W/C and UCS

The influence of W/C ratio on wet shotcrete mainly reflected the variation of its internal initial porosity at low temperature. Studies show that hydration product volume is approximately 2.2 times of dehydrated particles in the process of cement hydration (Alexander et al., 1968; Zhang et al., 2004). In the present work, the hydration degree of cement determined the pore structure distribution in shotcrete. Pore size and porosity decreased as the hydration degree of cement deepened.

Porosity in the wet shotcrete decreased with the increase of hydration reaction and the reduction of W/C ratio, which agrees with the experimental results. Under the same hydration (curing environment and cement content), the porosity of wet shotcrete was only determined by the W/C ratio. Thus, concrete strength was only determined by W/C ratio in this case. The wet shotcrete was a compound product of hydrated cement slurry and aggregate. Thus, the interface bonding property of slurry and aggregate in shotcrete affected the macro mechanical properties of wet shotcrete. Generally, aggregate is an inert material without chemical reaction. The strength of cement slurry and aggregate interface is mainly related to W/C ratio and the surface morphology of the aggregate.

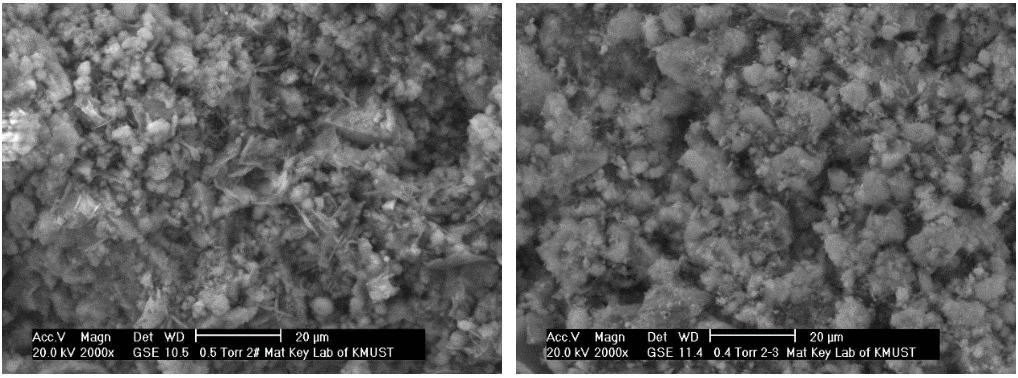
On the basis of the experimental results and theoretical analysis, the W/C ratio of wet shotcrete in a mine should be controlled below 0.4 with a slump ranging from 15 cm to 20 cm.

5.3. Analysis on microstructure

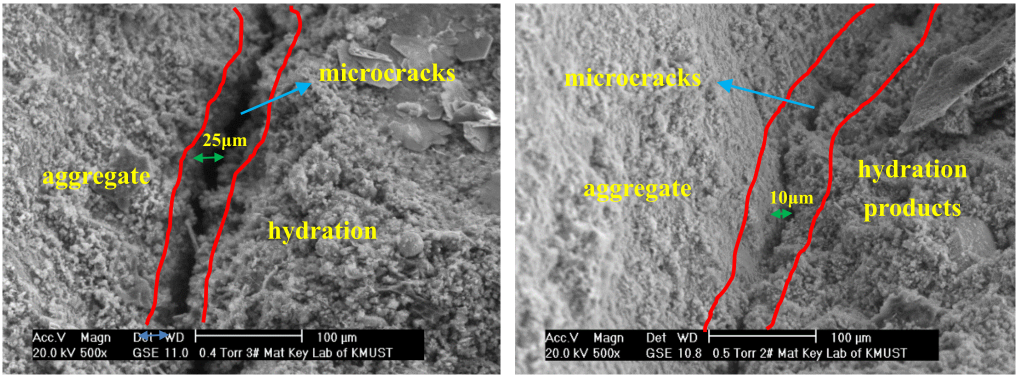
Wet shotcrete is an artificial multiphase composite made up of gravel, cement, water reducing agent, accelerating agent, fiber, and water. From the macroscale perspective, wet shotcrete contains water mud, sand, and fiber. From the microstructure perspective, wet shotcrete is composed of cement colloid, $Ca\ (OH)_2$ crystals, unhydrated cement particles, gel porosity, capillary porosity, pore water, and air bubbles. The microstructure of wet shotcrete considerably influences its macroscopic mechanical properties (Chang et al., 2009; Yao et al., 2015). Excellent microstructure is an internal cause of high strength of wet shotcrete in the early stage. The influence of temperature, cement content, and W/C ratio on the strength of wet shotcrete is affected by the hydration of cement in wet shotcrete, which results in the variation of the microstructure of wet shotcrete. SEM was used in the present work to analyze the microstructure of shotcrete under the influence of temperature, cement content, and W/C ratio, as shown in Fig. 6.

From the figure, the microstructure of wet shotcrete differs considerably in different mix proportions. As the curing temperature, cement content, and curing age increased, the pores of microstructure of shotcrete gradually decreased, the structures became increasingly compact, the microcracks decreased, and the bonding degree of cement slurry and aggregate constantly increased. The 7-day microstructures of wet shotcrete with cement content of 430 kg/m^3 and curing temperatures of 5°C and 15°C are shown in Figs. 6a and 6b, respectively. The figures indicated that cement hydration increased and hydration product enlarged with the increase in curing temperature. The 7-day microstructure of wet shotcrete with cement content of 415 kg/m^3 is shown in Fig. 6c. From the figure, microcrack and large amount of unhydrated cement particles existed at a width of 20-25 μm, with a loose overall structure. The 7-day microstructure of wet shotcrete with cement content of 430 kg/m^3 is shown in Fig. 6d. From the figure, the width (approximately 10 μm) of the microcrack obviously decreased compared with that in Fig. 6c with a compact space network structure. Along with the increase of curing ages and the deepening degree of cement hydration, microcracks in the shotcrete closed up gradually to integrate with the surrounding hydration products (Fig. 6e). In Fig. 6f, the shotcrete microstructure was compact with good sectional bonding between cement slurry and aggregate with unnoticeable microcracks due to the completed hydration reaction caused by high curing temperature, long curing ages, and large cement content.

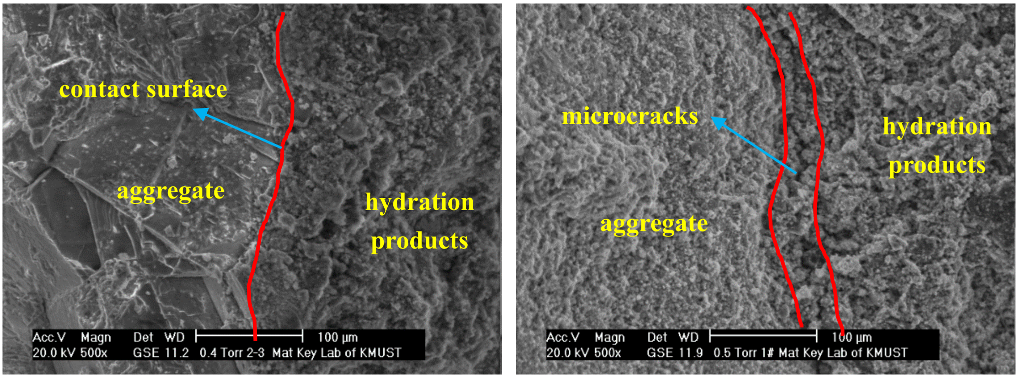
Cement slurry and bonding strength of aggregate are the key factors in wet shotcrete. The bonding strength of the aggregate might vary with different temperatures, cement contents, and W/C ratios. As shown in Figs. 6c-6f, aggregate interfaces have distinct differences under different proportions and curing conditions. When the curing temperature was 5°C at 7 days, apparent cracks existed in the cement slurry and aggregate interface (Fig. 6c). When the curing temperature was 15°C at 28 days, the cement slurry and the aggregate were bonded entirely (Fig. 6e). Different thermal expansion coefficients between cement slurry and aggregate also led to the crack of wet shotcrete interface and the decrease in macro strength. The thermal expansion coefficient of the cement slurry and aggregate were between 11×10^{-6}°C and 20×10^{-6}°C (Jiang et al., 2013; Bonnel et al., 1950) and 5×10^{-6} and 13×10^{-6}°C (Qian et al., 2009; Huang et al., 2010). Moreover, the hydration process of shotcrete belonged to the exothermic reaction. Thus, the temperature differences between increasing wet shotcrete and curing environment raised the interface cracks.



(a) 5°C, 7 days, 430 kg/m^3 (b) 15°C, 7 days, 430 kg/m^3



(c) 5°C, 7 days, 415 kg/m^3 (d) 10°C, 7 days, 430 kg/m^3



(e) 15°C, 28 days, 430 kg/m^3 (f) 10°C, 7 days, 445 kg/m^3

Fig. 6. SEM images of wet shotcrete (W/C:0.48)

6. Engineering application

6.1. Proportioning optimization of wet spraying material

The laboratory experiment results confirmed the material mixing proportion of wet shotcrete in a mine under low temperature, as shown in Table 3. During material mixing, the W/C ratio should be controlled below 0.46. The content of fine particles in the aggregate should be strictly controlled by adopting low-temperature-resistant water-reducing agent and low-temperature water-reducing agent and accelerating agent of BASF. The site shotcrete sampling experiments showed that the 28-day UCS of spraying materials was up to 26.3 MPa on average with a 45.7% increase from that before optimization regarding the strength of spraying layer.

TABLE 3

Mix Proportion of wet shotcrete

Cement **kg/m^3**	**Aggregate** **kg/m^3**	**Water** **kg/m^3**	**Fiber** **kg/m^3**	**Superplasticizer** **kg/m^3**	**Accelerator** **kg/m^3**
430	1733	194	6.0	3.5	3.5

6.2. Optimization of wet shotcrete technology

(1) Elevated temperature: A water heating boiler can be constructed next to the concrete mixing station to heat the materials to 40°C-50°C before mixing, making the slurry temperature to be maintained above 20°C to ensure effective hydration of cement. Raw materials, such as gravel and cement, can be kept indoors for insulation to ensure consistency between the temperature during material mixing and the room temperature. Underground ventilation system can be optimized to improve underground temperature to develop the strength of the spraying layer.

(2) Strong mixing: Hydration reaction, ion migration rate, and solution degree decrease at low temperatures. Thus, cement slurry can evenly wrap the aggregate by increasing the mixing time.

(3) Understanding of geological condition of roadways: Information about the rock mass structure and seepage characteristics of the roadway working surface before wet concrete spraying should be obtained. Corresponding water content and accelerating agent should be increased to improve the strength of the spraying layer in the early stage.

7. Conclusions

On the basis of the study of temperature effect on wet shotcrete of the mine in this study, the following conclusions can be drawn.

(1) The fishbone diagram indicates that the essential influencing factor of low strength and poor crack resistance of the wet shotcrete of the mine is low temperature, which is caused by short mixing time, large W/C ratio, failure of water reducer and accelerator, and many other problems.

(2) The UCS of wet shotcrete decreases with the temperature different ages. When the temperature drops from 10°C to 5°C, the 7-day compressive strength shows the sharpest drop. Temperatures above 15°C is favorable for later gain in strength.
(3) In a cold environment, low W/C ratio benefits wet shotcrete. A high W/C ratio contributes to strength development on the latter part. W/C ratio results in low compressive strength by influencing the internal initial porosity and aggregate interface bonding strength of wet shotcrete.
(4) SEM observation indicates that as the curing temperature, cement content, and age of curing increase and cement hydration reaction is completed, the spatial network structure of the wet shotcrete becomes increasingly compact, its internal microcracks gradually become close, and the aggregate interface becomes closely bonded. When the temperature is lower than 10°C, the aggregate interface is more likely to produce significant microcracks depending on different coefficients of thermal expansion.

This study analyzed the reasons for the low strength and poor crack resistance of wet shotcrete of the mine in question from merely the mixing proportion and microscopic morphology of the wet shotcrete. However, the cracking mechanism of the supporting structure based on its thermal stress and structural failure was not analyzed, which is a limitation of this study.

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