Method of detecting and evaluating compressive strength of in-service shaft wall concrete

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Abstract: In order to detect and comprehensively evaluate the wall compressive strength of the in-service shaft lining, the laboratory test and the on-site ultrasonic-rebound comprehensive method are used to test the compressive strength of the concrete wall in the main inclined shaft of a coal mine. The results show that the result value in laboratory test of the wall concrete block is 35.3MPa, and the average value by the rebound method is 40.57MPa, while the estimated value detected by the ultrasonic-rebound method is 34.3MPa; The results by laboratory test, rebound method and ultrasonic-rebound comprehensive method are comparatively analyzed, and through comprehensive analysis, the test results by the ultrasonic-rebound comprehensive method have higher confidence, with the estimated value likely closer to the actual strength and meeting the testing requirements; The test results could provide data support for the stability and safety assessment of the shaft wall.

1. Introduction
The mine shaft is the throat entering deep mining, as well as a safe passage entering deep mining. The in-service shafts locate in the rock stratum and multi-phase geological body which due to different distribution characteristics, complex in-service environment, and the characteristics of multi-level, nonlinearity and irreversibility, seriously affects the safe operation of the mine \cite{1}. Therefore, the stability, reliability and safety of the wall of the in-service shafts are of great significance to the mine production.

At present, the problems of shaft degradation such as instability or inclination of the service shafts, permeable shaft walls, circumferential cracking of the shaft walls, exposed steel bars, corrosion of the shaft walls and the impact tendency of the concrete in the shaft wall are becoming more and more prominent \cite{2}. Therefore, the safety evaluation on the reinforced concrete shaft wall structure which has been in service for many years must consider the deterioration of the wall concrete under the conditions of multi-year service. At the same time, with the increase of mining depth, the growth of energy extraction and the demand of national strategies, the stability of the shafts is a complex and important issue that needs to be studied intensively and one of the important basic research works to ensure mine construction and normal production \cite{3}. Second, in order to better promote the
transformation and upgrading of shut-down mines and promote the comprehensive utilization of special underground space in China, the shaft is also the only way to enter the underground space. Therefore, the primary task of reusing the closed mine shafts is to perform security detection on the strength of the shaft walls which has severed in the whole mining process.

For the method of measuring wall concrete strength, the Concrete Strength Inspection Standard GB/T50107-2010 stipulates that the strength of the wall concrete can be measured by core drilling method, but the core drilling method will destroy the integrity of the shaft wall structure and even cause the wall cracking, resulting in further deterioration and damage of the shaft walls. Moreover, for the shaft wall point that has already been discharged, the core drilling method is extremely unsuitable 

Ultrasonic testing technology can measure the concrete properties of the shaft wall without damaging the structural integrity and appearance; The detection is carried out by using an ultrasonic instrument and a rebound hammer. In the same measurement area of the component concrete, the ultrasonic acoustic parameters and the rebound value are respectively measured, and the concrete strength of the measurement area is estimated with the established strength formula. Compared with the single rebound method, the ultrasonic testing technology has the advantages of small influence on concrete age and water content, high detection precision, wide application range, and enabling to comprehensively reflect the actual quality of concrete structure.

In summary, the non-destructive testing technology which is used to measure the concrete strength of the in-service shaft walls, plays an important role in evaluating the safety and stability of the shafts. In this paper, the main inclined shaft of Shanghai Temple coal mine in Inner Mongolia is taken as the research background. Due to the lack of original construction materials, it is impossible to judge whether the walls in the section of the existing concrete block lining meets the requirements of the force. Various methods were used to test and comprehensively analyze the strength of the wall concrete block, which provides data support for the stability and safety evaluation of the shaft walls.

![Figure 1. Sample preparation of shaft wall concrete block](image)

2. Test methods and scheme

2.1 Sample preparation for laboratory test
The test stones required in this test are taken from the fork walls of the main inclined shaft mouth, with the blocks consistent with the shaft wall blocks. The cutting for the blocks and the test on their physical and mechanical properties are carried out. In the National Engineering Laboratory of Coal Mine Deep Well Construction Technology, block cutting and corresponding mechanical experiments were carried out on the blocks taken at the site. The sample preparation process is shown as Figure 1. Three cubic blocks of 100mm×100mm ×100mm are shown in Figure 1. The densities of the test block were 2342.76kg/m³, 2342.8kg/m³, 2368.3 kg/m³, respectively, and the average density was 2334.27kg/m³.

2.2 Test equipment and parameters
This test adopted GAW-2000 rock rigid compression testing machine produced by Changchun Chaoyang Instrument Co., Ltd., with a maximum pressure of 600kN, providing axial loading and unloading; Uniaxial loading test was performed according to the Concrete Strength Inspection and Evaluation Standard GB/T 50107-2010 for; The whole process loading rate in this testing was 0.006mm/min, as shown in Figure 2. The NM-4A ultrasonic detection analyzer produced by Beijing Kangkerui Co., Ltd. was used as the ultrasonic detector, to carry out the acoustic wave test. The sensor and the sample are coupled by glycerin, and the average longitudinal wave velocity of the three test
blocks is 25mm/µs.

Figure 2. Uniaxial compression test system for shaft wall block concrete

2.3 On-site testing instruments and methods
The main inclined shaft wall was built in 2005 and has been in service for 13 years. It can only provide one detection surface on the inner edge of the shaft wall. Therefore, the strength of the concrete block wall can be only measured by the plane testing method. The plane test surface can be the pouring side face, surface or undersurface. When the plane testing is performed, the ultrasonic wave propagates along the detection surface. The difference of the detection surface condition will inevitably affect the ultrasonic sound velocity. When the shaft walls could not be verified according to the actual situation on site, the block surface to be tested could be the pouring side face, surface or undersurface. When the measuring points are arranged, the clean and flat surface without honeycomb and pockmarks should be selected as much as possible to test. This on-site inspection used the ZC3-A rebound hammer and the NM-4A ultrasonic wave detector.

The ultrasonic-rebound area was a 200mm×200mm square, and each test area was arranged to test 9 rebound points, with the distance between two adjacent points of 100mm. The ultrasonic testing area was in the rebound detection area, with the upper and lower points arranged. Three measuring points were arranged in each testing area, and the distance between two adjacent points was 100mm. In order to reduce the data error, the average was taken from three-times tests of each group. The on-site testing layout is shown in Figure 3.

Figure 3. Ultrasonic testing area layout

2.4 Location selection for on-site detection
Considering the influence factors such as the characteristics of the stratigraphic interface, the location of the wall water outlet and the test conditions, the on-site ultrasonic-rebound test position was selected. According to the feasibility of the on-site test implementation, the specific test position of the main inclined shaft is shown in Table 1.

Table 1. On-site ultrasonic-rebound detection position of main shaft

| Burial depth (m) | Inclined length (m) | Number of test areas |
|-----------------|---------------------|----------------------|
| 23.6            | 63                  | 1                    |
| 32.6            | 87                  | 2                    |
| 103.9           | 277.5               | 1                    |
| 139.9           | 373.5               | 1                    |
| 162.39          | 433.5               | 2                    |
During the test, ultrasonic testing was performed first, then followed by rebound value testing. Among the 9 rebound values of each test area, 1 maximum value and 1 minimum value were eliminated, and the average rebound value was calculated by using the remaining 7 rebound values. The average sound velocity value was calculated using a total of 9 ultrasonic sound velocity values of the three groups. According to the concrete rebound representative value and the sound speed representative value of each test area in the shaft wall, the ultrasonic-rebound detection was carried out according to the relevant requirements of China Engineering Construction Standardization Association Standard “Technical Specification for Ultrasonic Rebound Comprehensive Method of Testing Concrete Strength”, CECS02:2005.

3. Analysis of test results

3.1 Uniaxial compressive strength analysis of shaft wall blocks

Figure 4 shows the uniaxial loading stress-strain curve of the wall concrete cube. In the initial stage of the wall concrete uniaxial loading, due to insufficient vibrating effect during the shaft wall block construction process, the internal porosity of the test block is high. During the compacting phase, the amount of deformation increases and the stress increases slowly. The uniaxial compression process is mainly divided into five stages: pore and microcrack compaction stage, linear elastic strain stage, crack stable expansion stage, crack unsteady expansion stage and post-peak stage.

![Figure 4. Uniaxial stress - strain curves of concrete wall test block](image1.png)

It can be seen from the test results that the peak strength of the test block 1 is 39.3 MPa, the peak strength of the test block 2 is 11.2 MPa, and the peak strength of the test block 3 is 35.1 MPa. The wall concrete test blocks are mainly dominated by brittle fracture, with a low residual strength after the peak. After the test block 2 is cut and formed, many internal defects emerge, and the self-degradation is serious, resulting in low compressive strength. The average uniaxial compressive strength of the wall concrete is 37.2 MPa. According to the provision 4.3.1 of the “Concrete Strength Evaluation Standard” GB50107-2010, the test of the concrete test piece stipulates the method for determining the representative value of each group, that is, the test result of the test piece with the side length of 100 is multiplied by the coefficient of 0.95. Therefore, the comprehensively evaluated strength of the wall block concrete is 35.3 MPa.

3.2 Failure characteristics analysis of the concrete test blocks in shaft wall

![Figure 4. Uniaxial stress - strain curves of concrete wall test block](image2.png)

(a) Collapse state of test block 1
Figure 5. Collapse states of concrete test blocks in shaft wall

In Figure 5, (a) and (b) are the collapse states of the test block 1 and the test block 2, respectively. The test blocks are mainly dominated by tensile damage, and the fracture crack mainly extends along the interface between the pebble and the mortar material, mainly dominated by main crack penetration failure, with a large number of secondary cracks existing and V-shaped damage in a small local area. The degree of fracture is relatively serious. From the test process, it can be found that the block concrete aggregate is mainly composed of pebbles, and the pebble particle size is poorly graded, with the poor vibrating density during the block making process. Therefore, defects such as micro-cracks and micro-pores of different scales and random distribution are formed inside the blocks, which leads to the fracture mode of the block structure formed by the pebbles and the mortar material. Destructive cracks mainly occur at the interface between the pebbles and the mortar material, and a few occur in the mortar material, while rare cracks damaged by the pebbles emerge. Therefore, the cementation degree of the pebbles and mortar materials as aggregate materials is a decisive factor influencing the strength of the blocks.

3.3 Test results of main shaft rebound value

It can be obtained from the mechanical test of the shaft wall block. The concrete block of the wall is a non-reinforced block, and the aggregate is pebbles with poor size grading, mainly dominated by the pebbles of large particle size. Each test area for rebound detection is a 200mm × 200mm square, and 9 rebound points are tested in each test area.

After removing 1 maximum value and 1 minimum value from the 9 rebound values of each test area, the average rebound value of each test area is calculated by using the remaining 7 rebound values, and the test results are shown as Tab 2. Therefore, the average value of all the test areas is taken during the test, to obtain the average value of all the test areas in the main shaft, 40.57 MPa.

Table 2. Main shaft on-site rebound test results

| Burial depth (m) | Inclined length (m) | Number of test areas | Test results/MPa |
|------------------|---------------------|---------------------|------------------|
| 23.6             | 63                  | 1                   | 33.14            |
| 32.6             | 87                  | 2                   | 39.64            |
| 103.9            | 277.5               | 1                   | 39.0             |
| 139.9            | 373.5               | 1                   | 42.43            |
| 162.39           | 433.5               | 2                   | 48.9             |
| 185.4            | 495                 | 2                   | 40.36            |

3.4 Main shaft ultrasonic rebound comprehensive method strength test results

Table 3. Main shaft on-site ultrasonic test results

| Buried depth (m) | Oblique length (m) | Number of test areas | Sound velocity (km/s) |
|------------------|--------------------|----------------------|-----------------------|
| 23.6             | 63                 | 1                    | 4.31                  |
| 32.6             | 87                 | 2                    | 4.72                  |
| 103.9            | 277.5              | 1                    | 4.82                  |
| 139.9            | 373.5              | 1                    | 4.65                  |
162.39 433.5 2 4.01
185.4 495 2 4.54

The sound velocity values of the main shaft wall test areas are measured by the ultrasonic plane testing method as shown in Table 3. According to the ultrasonic-rebound comprehensive detection theory, the ultrasonic velocity mainly characterizes the compactness of the internal structure of the concrete, reflecting the elastic properties of the concrete structure. The higher the sound velocity, the denser the internal structure and the stronger the strength [9]. The rebound method mainly characterizes the strength values of the carbonization thickness range of the concrete surface, reflecting the plastic property of the concrete structure [10].

According to the concrete rebound representative value and sound speed representative value of each test area of the component, the concrete compressive strength equivalent value of each test area is calculated according to the relevant requirements of the China Engineering Construction Standardization Association Standard “Technical Regulations for Testing Concrete Strength by Ultrasonic Rebound Comprehensive Method” CECS02:2005. After calculation by mathematical statistics method, the estimated concrete strength of the test block is obtained.

When the coarse aggregate is pebbles, according to equation (1), the compressive strength of each test area can be obtained.

\[ f_{Cu,i} = 0.0056v_{ai}^{1.439}R_{ai}^{1.769} \]  

where: \( f_{Cu,i} \) is the equivalent value of concrete compressive strength in the i-th measurement area, MPa; \( v_{ai} \) is the representative value of ultrasonic sound velocity, km/s; \( R_{ai} \) is the rebound representative value, MPa; 0.0056, 1.439, 1.769 are curve parameters.

Based on the above analysis, the ultrasonic test strength of the main shaft wall block concrete can reach 34.3MPa.

Table 4 Main shaft on-site ultrasonic-rebound test results

| Buried depth (m) | Inclined length(m) | Number of test areas | Ultrasound-rebound |
|-----------------|--------------------|----------------------|-------------------|
| 23.6            | 63                 | 1                    | 22.42355          |
| 32.6            | 87                 | 2                    | 35.08237          |
| 103.9           | 277.5              | 1                    | 35.13064          |
| 139.9           | 373.5              | 1                    | 38.72634          |
| 162.39          | 433.5              | 2                    | 40.22538          |
| 185.4           | 495                | 2                    | 34.24672          |

4. Discussions

It is of great practical significance to accurately judge the existing strength of the wall concrete and quantify the shaft wall fracture index. The reasonable evaluation on the structural strength states of the wall concrete blocks, is an important prerequisite for early warning and the treatment of the wall rupture accident. The wall concrete blocks under the complicated underground environment for a long time, are affected by natural factors such as temperature and groundwater. Moreover, under the effect of high level and high vertical force for a long time, its strength will be damaged and weakened to a certain degree. After several years of service, the strength grade of the wall block concrete material will inevitably decrease to some extent. Therefore, how to obtain the current strength grade and reliability of concrete shaft wall simply and accurately is great significant for each block safety production. The ultrasonic-rebound comprehensive detection and analysis method is applied to the strength evaluation on the wall concrete blocks, which not only avoids the damage to the wall caused by the traditional method, but also has the advantages of simple operation and taking less time in occupying the shaft, serving as an ideal method to test the strength of the concrete blocks in shaft wall.

The ultrasonic-rebound comprehensive method can theoretically avoid the influence of the surface factors of the shaft wall concrete and more accurately determine the concrete strength.
The strength value of the wall concrete detected by the rebound method is slightly higher than that detected by the ultrasonic-rebound comprehensive test method. When performing the rebound method, due to the choice of position, the rebound point may be just on the pebbles, so the rebound value is likely higher than the block strength value. And at the meantime, due to the uneven and porous characteristics of the block surface, the rebound point may also occur at the holes or at the edge of the holes, resulting in the rebound value lower than the strength of the blocks. The two types of extreme conditions are difficult to avoid during the test. The ultrasonic-rebound comprehensive detection method uses the transmission of ultrasonic velocity inside the concrete to reflect its compactness, so its detected value is closer to the actual strength. In this on-site test, ZC3-A rebound hammer and NM-4A ultrasonic detector were used. Through comprehensive analysis, the strength of the main shaft wall block concrete obtained by ultrasonic test can reach 34.3MPa; As can be known from the test results, the inner wall of the main shaft at the inclined length of 63m and 277m has relatively low compaction rate, where the areas are mainly of water seepage and water leakage and supposed to be monitored emphatically. The test results are mainly the strength of the wall block. During the on-site investigation, it is found that the mortar joint between the local blocks of the wall is cracked, and the stratigraphic rock can be observed, with seriously deteriorated structure of the wall. Therefore, the test results can only characterize the strength of the concrete wall block, and further calculation and analysis is required for the overall bearing structure strength of the block.

5. Conclusions

(1) The ultrasonic-rebound comprehensive method can avoid being affected by surface factors of shaft wall concrete and more accurately determine the concrete strength, which is an ideal method to test the block strength of the shaft wall concrete.

(2) The compressive strength test result of the shaft wall concrete in the laboratory is 35.3 MPa. The mean value of rebound method is 40.57 MPa, and the estimated value detected by ultrasonic-rebound comprehensive method is 34.3MPa. The results of the laboratory test, the rebound method and the ultrasonic-rebound comprehensive method are comparatively analyzed, and the results detected by the ultrasonic-rebound comprehensive method are comprehensively analyzed and present a high degree of confidence.

(3) The test results show that the test results of the main shaft inner wall at the inclined length of 63m and 277m are relatively low, indicating that the internal compactness rate of the concrete at the test location is poor, and the areas are of water seepage and water leakage and supposed to be monitored emphatically.

Acknowledgments
This paper is supported by the State Key Research Development Program of China (Grant No. 2016YFC0600801), key project supported by National Natural Science Foundation of China (51534002) and the Special Funds for Technological Innovation and Entrepreneurship of China Coal Science and Engineering Group Co., Ltd.(2018MS026). The authors thank the anonymous reviewers for their valuable and instructive comments that greatly help improve the quality and completeness of this paper.

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