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Research on the strength detection methods of railway tunnel linings

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Abstract

Purpose – For the commonly used concrete mix for railway tunnel linings, concrete model specimens were made, and springback and core drilling tests were conducted at different ages. The springback strength was measured to the compressive strength of the core sample with a diameter of 100mm and a height-to-diameter ratio of 1:1. By comparing the measured strength values, the relationship between the measured values under different strength measurement methods was analyzed.

Design/methodology/approach – A comparative test of the core drilling method and the rebound method was conducted on the side walls of tunnel linings in some under-construction railways to study the feasibility of the rebound method in engineering quality supervision and inspection.

Findings – Tests showed that the rebound strength was positively correlated with the core drill strength. The core drill test strength was significantly higher than the rebound test strength, and the strength still increased after 56 days of age. The rebound method is suitable for the general survey of concrete strength during the construction process and is not suitable for direct supervision and inspection.

Originality/value – By studying the correlation of test strength of tunnel lining concrete using two methods, the differences in test results of different methods are proposed to provide a reference for the test and evaluation of tunnel lining strength in railway engineering.

Keywords Tunnel lining, Concrete, Strength, Rebound method, Core drilling method

Paper type Research article

1. Preface

Insufficient strength of tunnel lining concrete is a red line for safety and quality management in railway construction projects, and there are numerous incidents where structures are scrapped due to concrete failure (Hu, Li, & Zhang, 2012). There are many factors that affect the strength of concrete, such as the manufacturer and origin of the raw materials, the curing process during construction and the testing method when testing the strength (Ma, Chen, & Hu, 2005). These factors cause the measured strength of the concrete to fluctuate within a certain range (Hu, Zhang, & Dong, 2011). The fluctuation of concrete strength is bound to affect the stability of the structure and its subsequent service life (Hu & Zhang, 2011). Therefore, using appropriate testing methods to test and monitor the strength of concrete is an important part of ensuring the safety of large structures such as tunnels or Bridges (Yang, Yang, & Chen, 2008).

In the construction and maintenance of railway tunnels, concrete strength testing is a key link to ensure structural safety, among which the rebound method and core drilling method are commonly used testing methods (Zhao, Tang, & Ni, 2006).

The rebound method is highly favored in engineering due to its significant advantages. It is easy to operate, has relatively low technical requirements for inspectors, and has a wide range of application conditions (Ma & Chai, 2019). It can be quickly mastered for both new and existing tunnel inspections. Moreover, the results are read quickly, and a large amount of data can be obtained in a short time, greatly improving the efficiency of the inspection. Therefore, in conventional concrete strength tests, the rebound method is often the preferred approach (Jiang,

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Wu, & Ma, 2020). However, the rebound method also has obvious limitations. Because the concrete lining is affected by factors such as carbonation and surface float, there is often a situation where the surface strength is lower than the internal strength (Du, Zhu, & Zhao, 2021). The rebound method, which mainly calculates the strength of concrete by measuring the hardness of its surface, in this case the test results will deviate from the actual strength, resulting in inaccurate testing.

In contrast, the core drilling method can effectively make up for the shortcomings of the rebound method. It conducts strength tests by drilling core samples from the concrete structure. The test results are highly accurate and can directly and accurately reflect the actual strength of the concrete (Zhai, Wang, & Zhu, 2019). Moreover, this testing method is not affected by surface conditions, whether it is a carbonized layer or a floating slurry layer, it will not affect the reliability of the test results. However, the core-drilling method has its drawbacks. Its local damage detection method can cause a certain degree of damage to the tunnel structure. If used on a large scale, it may affect the structural safety and service life of the tunnel, so the detection range cannot be expanded at will (Hou, 2017).

In order to select the detection method more scientifically, this paper conducts a comprehensive comparative analysis of the rebound method and the core drilling method based on carefully prepared specimens and strength tests, combined with actual railway tunnel engineering examples (Yang, Yuan, & Li, 2009). By delving into the applicable conditions and testing the effects of the two methods, it aims to provide valuable references for the strength testing of tunnel linings and ensure the safe operation of railway tunnels.

2. Model preparation and testing

In railway tunnel construction, it is crucial to accurately grasp the variation law of tunnel lining concrete strength and the applicability of different detection methods. For this purpose, we carefully made model specimens based on the commonly used concrete mix ratios for railway engineering tunnel linings to conduct systematic experimental research (Wang & Wang, 2013).

After the model was made, we strictly followed the established test plan and conducted rebound and core drilling tests on the model at different ages. For the rebound test, we used a professional rebound instrument to strike the model surface at key ages of 14 days, 28 days, 56 days and 90 days to accurately measure the rebound value at each age and calculate the corresponding rebound method to estimate the strength based on relevant standards and formulas.

For the core-drilling test, considering the destructive effect of core-drilling on the specimen and the representativeness of the test, we used a core-drilling machine to drill standard core samples with a diameter of 100mm and a height-to-diameter ratio of 1:1 from the model at the ages of 28d, 56d and 90d, and then conducted compressive strength tests on the core samples on a pressure testing machine to obtain accurate compressive strength values.

By comparing and analyzing the estimated strength by the rebound method and the compressive strength measured by the core drilling method at different ages, we were able to clearly observe the growth pattern of concrete strength with age and, at the same time, explore the intrinsic relationship between the strength values measured by different testing methods, providing a scientific and reliable basis for the strength testing of railway engineering tunnel lining concrete (Zhang, 2014).

2.1 Model preparation

Make concrete models of strength grade C35 with dimensions (length × width × height): 250cm × 50cm × 40cm (Model A) and 100cm × 50cm × 40cm (Model B). The concrete mix proportions are shown in Table 1.

In Table 1, the cement is P.O42.5 cement from a certain cement limited company, the sand is sand with a fineness modulus of 2.8 from a certain watersand plant, the crushed stone is graded crushed stone with a maximum particle size of 31.5mm from a certain quarry, the gradation composition is 5–10mm, 10–20mm and 16–31.5mm in a ratio of 2:5:3 and the admixture is Class F grade I admixture. Admixture one is SPC-100 polycarboxylic acid high performance water reducer.

Table 1. Model concrete mix proportions

Material names	Cement	Sand	Crushed stones	Water	Admixtures	Rubber material Total quantity	Admixtures
Ingredients per cubic meter (kg)	276	789	203.4/ 508.5/ 305.1	160	117	390	3.90

Source(s): Author's own work

2.2 Strength test

Draw test areas of the same size on the concrete model specimens for use in 14d, 28d, 56d and 90d age tests. At 14d age, only the rebound test is conducted without core drilling. For the rest of the ages, after the rebound test is completed, the core drilling test is carried out.

2.2.1 Determination of the rebound strength of the concrete model. There is a series of rigorous and crucial preparations and operating procedures that must be strictly followed before using the rebound tester for concrete strength testing. First of all, the verification date of the rebound tester must be carefully checked to ensure it is within its validity period, which is the basis for ensuring accurate and reliable test results. Then, calibrate the rebound instrument with a professional anvil to ensure it is in the best working condition. When entering the test phase, the operator must ensure that the axis of the rebound instrument is always perpendicular to the concrete test surface, which is crucial for obtaining accurate rebound values. During the pressure application process, use both hands to apply force slowly to avoid slippage and ensure the accuracy of the readings. For the division of the rebound detection area, select ten zones on the concrete surface, each measuring 10cm $\times$ 10cm, and the distance between the zones and the boundary should be no less than 5cm. In each test area, 16 test points should be evenly distributed, with a distance of no less than 2cm between each point. This uniform distribution of test points can provide a more objective and comprehensive feedback on the test results and accurately reflect the overall strength of the concrete. In addition, the number of areas for the carbonation depth test should be no less than 30% of the total number of areas. If the surface of the test area is the original concrete surface but has defects such as unevenness or honeycomb pitting, it needs to be ground and leveled in advance. Finally, conduct in-depth analysis and scientific assessment of the data obtained from the test in accordance with the Technical Code for Quality Inspection of Concrete Entities in Railway Engineering TB 10433–2023.

2.2.2 Determination of core strength of the concrete model. In railway engineering concrete strength testing, a scientific and rigorous testing process was adopted to accurately obtain the strength data of concrete at different ages. The advanced DD200 drill rig was used for the sampling operation, which was stable in performance and high in precision and could effectively guarantee the quality and efficiency of core sampling. On the day the concrete age reaches 28 days, 56 days and 90 days, the rebound test is carried out immediately. After the rebound test was completed, a 100mm diameter concrete core sample was drilled on the same test section using a DD200 drill. To ensure the systematicness and comparability of the data, core sampling was carried out by age, with two sets of precise core sampling for each age, resulting in a total of six core samples. The extracted core samples need to be finely processed. First, the core samples are cut to the appropriate length by professional cutting equipment, then finely ground with grinding tools, and finally standard concrete specimens with a height-to-diameter ratio of 1:1 are produced to meet the requirements of the compressive strength test. To minimize the uncertainty of the test results caused by objective or human factors, the same drill rig is used for sampling throughout the test process and fixed and experienced professionals are arranged for sampling and core sample processing operations. Through such strict control measures, the actual strength values of concrete at different ages can be more objectively and accurately reflected, providing a reliable basis for engineering quality assessment.

3. Results and analysis

3.1 Compressive strength analysis

At the ages of 28 days, 56 days and 90 days, core samples were taken from the concrete model. Two groups of six core sample specimens were processed at each age for compressive strength tests. The compressive strength results of this test were consistent. The average of the strength test values of the two groups of specimens was taken as the cube compressive strength corresponding to a certain age. The test results are shown in Table 2.

With age as the abscissa and core specimen compressive strength as the ordinate, draw the curve of compressive strength with age as shown in Figure 1.

In Table 2 and Figure 1, the strength of the model concrete increased significantly after 28 days of age, with a logarithmic curve growth pattern and a correlation coefficient of 0.99. During the period from 28d to 90d, the strength increased by 9.7MPa, which was 17.8% of the 28-day strength value. Compared with the 56d age, the strength increased by 4.9MPa at 90d, which was 8.2% of the 56d strength value.

According to the Railway Concrete Strength Inspection and Evaluation Standard TB10425-2019, the age for strength assessment of reinforced concrete and plain concrete should be 56d or longer. When the design documents have specific requirements for the age of concrete strength assessment, the design provisions shall be followed. “56 days or longer age” takes into account the harmonization of the standard. In supervisory testing or red line inspection, it is feasible to carry out section 5.4.1 of “Railway Concrete” TB/T3275-2018 to test the compressive strength of railway concrete at 90 days of age.

3.2 Rebound strength analysis

Rebound tests were conducted on the concrete models at ages 14 days, 28 days, 56 days and 90 days, and the estimated strength by the rebound method (MPa) was calculated. The test results are shown in Table 3.

Table 2. Compressive strength of core samples of concrete models at different ages

Serial number	Age (d)	Strength (MPa)
1	28	54.5
2	56	59.3
3	90	64.2

Source(s): Author’s own work

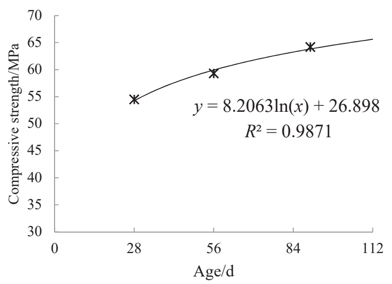

Figure 1. Strength–age relationship curve of core specimens. Source(s): Author’s own work

Table 3. Estimated rebound Strength of concrete models at different ages

Serial number	Age (d)	Strength (MPa)
1	14d	41.1
2	28d	45.5
3	56d	52.5
4	90d	55.6

Source(s): Author's own work

3.3 Comparative analysis of strength tests by two methods

It can be seen from the data in Tables 2 and 3 that the strength measured by the rebound method is less than the compressive strength measured by the core drill. The strength difference of this model at 28 days, 56 days and 90 days is 6.8MPa–9.0MPa. With age as the abscissa and strength values as the ordinate, a comparison of strength between the rebound method and the 100mm diameter 1:1 core sample is plotted as shown in Figure 2.

It is clearly shown from the comparison data of strength obtained by the rebound method and the core drilling method in Figure 2 that the estimated strength measured by the rebound method is significantly lower than the compressive strength value of the concrete core sample with a diameter of 100mm and a height-to-diameter ratio of 1:1 drilled. There are multiple reasons behind this difference. During the concrete construction process, to meet the construction requirements such as high fluidity and pumpability of the pumped concrete, a certain amount of admixtures are often added, along with mineral admixtures such as fly ash. The addition of these materials increases the proportion of gel materials and alters the microstructure and composition of the concrete. In terms of surface properties, the change in the proportion of gel materials leads to a reduction in the surface strength of the concrete. Also, the depth of carbonation is an important factor affecting the results of the rebound test. After carbonation of concrete, its surface hardness changes. The rebound method calculates strength based on surface hardness, and the presence of carbonation depth interferes with this calculation process, resulting in a lower strength value measured by the rebound method.

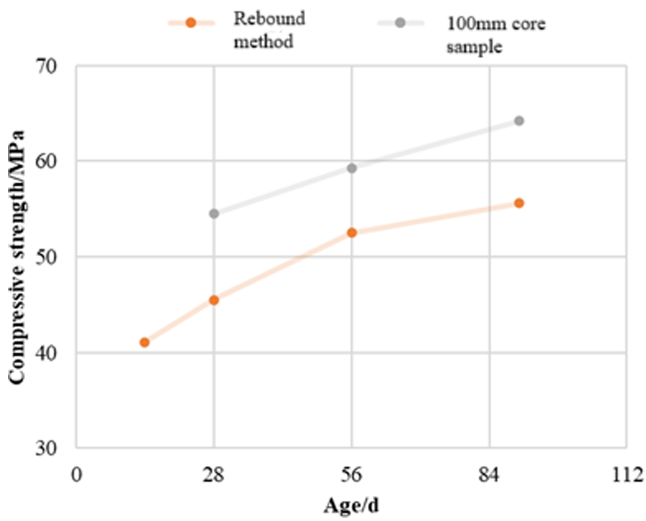

Figure 2. Comparison of strength between the rebound method and the core drilling method for concrete models. Source(s): Author's own work

The rebound method has the significant advantage of being simple and easy to operate. Inspectors can get started after a simple training and can quickly make a preliminary determination of the strength of concrete. Therefore, it performs well in many application scenarios, especially for large-scale surveys of the strength of structures, and can efficiently obtain the overall distribution of concrete strength. However, we must also be clearly aware that due to the many influencing factors mentioned above, when using the rebound method to test the strength of concrete, we cannot simply rely on the rebound value to determine whether its strength is qualified. For areas where strength is questionable, where the rebound test results do not meet expectations or where there are high requirements for structural safety, the core drilling method should be used for verification. By directly obtaining the actual strength data inside the concrete through the core drilling method, it ensures that the testing and evaluation of the strength of the structure is objective, accurate and reliable.

4. Engineering applications

In the construction and maintenance of railway tunnels, concrete strength testing is a key link to ensure structural safety and quality. Among them, the core drilling method and the rebound method, as two commonly used testing methods, each have their unique advantages and limitations.

The core drilling method can directly drill core samples from concrete structures and visually reflect the strength of concrete through laboratory tests. Its test results have high accuracy and reliability. However, this method also has obvious shortcomings. First, the core-drilling process causes irreversible damage to the concrete structure, affecting its integrity and durability. Secondly, the core-drilling operation takes a long time, and the entire process from drilling to sampling to laboratory testing is rather cumbersome, resulting in low testing efficiency. In addition, the core drilling method requires high equipment and labor costs and the test results can only reflect the local strength of the concrete and cannot provide a comprehensive assessment of the overall structural strength. Therefore, it is not suitable for large-scale testing work.

In contrast, the rebound rule to some extent makes up for the shortcomings of the core drilling method. The rebound method is easy to operate and can be mastered by inspectors after a simple training. They only need to use a rebound instrument to strike the surface of the concrete and calculate the strength of the concrete by reading the rebound value. The result reading is convenient and fast, greatly improving the inspection efficiency. At the same time, the rebound method is a non-destructive testing method that does not cause any damage to the concrete structure and has a low cost, making it very suitable for large-scale census work.

In order to further study the feasibility of the rebound method in railway engineering quality supervision and inspection, relevant departments selected some under-construction railways to conduct comparative tests of the core drilling method and the rebound method for tunnel lining concrete. The test covered 105 slabs of tunnel lining concrete from eight railway lines and was widely representative. The testing area covered South China and Southwest China, including Jiangxi, Fujian, Yunnan and Sichuan provinces, where there are significant differences in climate and geological conditions, which can more comprehensively reflect the applicability of the rebound method in different environments.

During the testing process, operations were carried out strictly in accordance with scientific and standardized procedures. Before the core test, the same slab of concrete is first tested by the rebound method, with ten test zones arranged for each slab of concrete to ensure that the test zones are evenly distributed and can accurately reflect the overall strength of the concrete. At the same time, each core sample hole should correspond to one rebound test area so that the results of the two testing methods can be compared and analyzed later. The processing of the test data shall be carried out in accordance with the relevant provisions of the Technical Code for Quality Inspection of Concrete Entities in Railway Engineering (TB 10433–2023) to ensure the accuracy and reliability of the data.

Through the analysis of a large amount of test data, the accuracy and reliability of the rebound method under different regions and engineering conditions can be further evaluated, providing a more scientific and reasonable basis for the testing of concrete strength in railway tunnels and promoting the continuous development and improvement of railway engineering testing technology.

A total of 105 sets of tunnel side wall lining core drilling tests were conducted in advance at the core drilling points. Each set tested ten test areas, among which 75 sets drilled cores at the rebound test area positions, totaling 225 pairs of data. Excluding the rebound strength conversion values greater than 60MPa, linear fitting was performed on the remaining 195 pairs of data. The linear fitting formula was: $f = 0.5158f_R + 22.4118(R^2 = 0.1240)$ The relationship graph was plotted with the estimated rebound strength on the abscissa and the core strength test on the ordinate, as shown in Figure 3.

It can be clearly observed from the data visualization results presented in Figure 3 that there is a positive correlation between the strength detected by the core drilling method and the rebound strength value, which means that, on the overall trend, as the rebound strength value increases, the strength detected by the core drilling method also tends to increase. However, the data distribution is rather discrete and not closely clustered near a straight line. The correlation coefficient R calculated is 0.51, which indicates a small correlation between the two and suggests that it is difficult to accurately infer the strength value detected by the core drilling method based solely on the rebound strength value (Zhang, 2006).

When the 105 sets of data were analyzed in depth, it was found that the average value of the estimated rebound strength of all components was 43.3MPa, while the average value of the estimated core strength was 46.8MPa. By comparison, it can be seen that the strength detected by the core method was slightly higher than that by the rebound method. The 105 sets of data were not randomly selected but were from the comparison of rebound and core drilling tests of the lining strength of eight newly built lines, covering lining structures under different lines and different construction conditions, with a certain degree of coverage, which can reflect the general situation of lining strength tests of newly built lines; it is also representative and can provide valuable reference for the selection of strength testing methods and the analysis of results for similar projects in the future, helping engineers to assess the strength of concrete structures more scientifically.

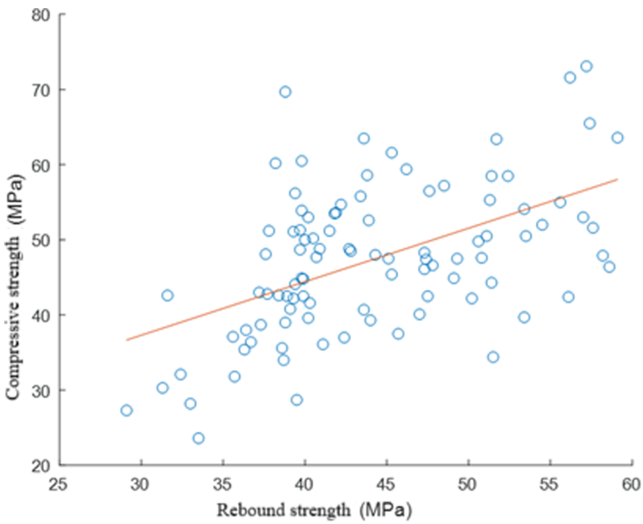

Figure 3. Diagram of the relationship between the core drilling method and the rebound method for testing the strength of tunnel linings. Source(s): Author’s own work

5. Conclusions

In engineering projects such as railway tunnels, concrete strength testing is a key link to ensure structural safety and quality. The core-drilling method and the rebound method are common testing methods and the correlation of their test results is of great significance to engineering practice. This study, through model tests and engineering applications, deeply analyzed the correlation between the two for the testing of concrete strength, mainly from three aspects: the growth law of strength with age, the relationship between the compressive strength of the core sample and the estimated rebound strength and the consistency of the assessment conclusions.

(1) The correlation of strength growth with age. Concrete strength varies with age, and different testing methods reflect this rule differently. The study found a positive correlation between rebound strength and core drilling strength. In the process of concrete construction, the rebound method is easy to operate, efficient, suitable for large-scale surveys and can quickly obtain the general situation of the surface strength of concrete. However, due to factors such as surface condition and carbonation, there may be some deviation in the test results of the rebound method. When there is doubt or controversy over the results of the rebound method, it is particularly necessary to use the core drilling method for verification. The core drilling method, which takes samples directly from the concrete structure for testing, can accurately reflect the actual strength inside the concrete and can be used as an effective supplement and verification method to the rebound method.

(2) The relationship between the compressive strength of the core sample and the estimated rebound strength. From the perspective of the correlation between the core drilling test and the rebound test strength, in the actual engineering comparison of the strength test of the 105-plate tunnel lining, the correlation coefficient of the strength test by the core drilling method and the rebound method is 0.51, which shows a large degree of dispersion. This indicates that there are certain differences in the test results of the two methods, and they cannot be simply substituted for each other. For the supervision and inspection of the State Railway Group, the aim is to make an accurate judgment on the quality of the project, and the inspection conclusion needs to be clear and reliable. Given the discreteness of the test results of the rebound method and the influence of multiple factors, it is advisable to use the core drilling method for concrete strength testing in supervision and inspection to ensure the accuracy and authority of the test results.

(3) Evaluation of conclusion consistency and age selection. In terms of the consistency of the assessment conclusions, factors such as winter construction and the development pattern of concrete strength are taken into account. There are differences in the development rate and final strength of concrete strength at different ages. The low-temperature environment in winter delays the hydration reaction of concrete and affects strength growth. To ensure the quality of the project and avoid disputes, it is feasible to test the strength of tunnel lining concrete at 90 days of age under supervision and sampling. The 90d age allows the concrete strength to develop fully, reduces strength errors due to insufficient age, makes the test results of the core drilling method and the rebound method more comparable and consistent and provides a more reliable basis for quality assessment.

To sum up, in concrete strength testing, the core drilling method and the rebound method should be reasonably selected based on different testing purposes and engineering conditions to ensure the quality of engineering construction.

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