Front. Struct. Civ. Eng. 2022, 16(9): 1170–1182
https://doi.org/10.1007/s11709-022-0874-5

RESEARCH ARTICLE

Quality evaluation of lightweight cellular concrete by an ultrasound-based method

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ABSTRACT The accuracy of subgrade quality evaluation is important for road safety assessment. Since there is little research work devoted to testing lightweight cellular concrete (LCC) by an ultrasound-based method, the quantitative relation between ultrasonic testing results and the quality of LCC subgrade is not well understood. In this paper, the quality of LCC subgrade was evaluated with respect to compressive strength and crack discrimination. The relation between ultrasonic testing results and LCC quality was explored through indoor tests. Based on the quantitative relation between ultrasonic pulse velocity and compressive strength of LCC, a fitting formula was established. Moreover, after the LCC became cracked, the ultrasonic pulse velocity and ultrasonic pulse amplitude decreased. After determining the lower limiting values of the ultrasonic pulse velocity and ultrasonic pulse amplitude through the statistical data, it could be calculated whether there were cracks in LCC subgrade. The ultrasonic testing results showed that the compressive strength of the LCC subgrade was suitable for purpose and there was no crack in the subgrade. Then core samples were taken from the subgrade. Comparisons between ultrasonic testing results of subgrade and test results of core samples demonstrated a good agreement.

KEYWORDS lightweight cellular concrete, subgrade, ultrasound testing, quality evaluation, crack discrimination

1 Introduction

Lightweight cellular concrete (LCC) is a porous cement-based material, which is made from cement slurry and high-volume pre-foams [1]. LCC forms a porous structure by introducing foam, and its characteristics differ from the characteristics of conventional dense concrete [2]. Due to its attractive properties such as lightweight, adjustable strength, porosity and significant fluidity [3], LCC has been successfully applied in weak soil replacement, highway embankment filling, underground cavity filling and other geotechnical engineering [4]. For example, as a backfill material behind abutments of expressway bridges, LCC can significantly reduce the self-weight load and the engineering land space [5]. Furthermore, LCC is an environmentally friendly material, and its physical and mechanical properties can be improved by adding industrial wastes such as fly ash, silica fume and polypropylene fiber. Liu et al. [6] investigated the strengthening mechanism of LCC mixed with fly ash with respect to the microstructure features including porosity and skeleton characteristics. Jitchaiyaphum et al. [7] tested the compressive strength, setting time, water absorption and microstructure of LCC mixed with fly ash and natural zeolite, and found that adding an appropriate amount of natural zeolite can reduce the setting time, total porosity and pore size of the paste. Bing et al. [8] employed fine silica fume and polypropylene fibers to improve the performance of LCC. Liu et al. [9] introduced green high-belite sulphoaluminate

Article history: Received Jan 18, 2022; Accepted Jun 14, 2022

cement calcined by use of whole industrial wastes into LCC, and tested its microstructure, crystallinity and mechanical properties. In the above-mentioned studies, it has been shown that LCC has broad application prospects in geotechnical engineering.

In recent years, owing to its attractive properties, LCC has been widely used to expand the range of available resources for producing subgrade filling [10]. Some research work has been devoted to applying LCC to subgrade construction. For example, Liu et al. [11] improved the mixture ratio of LCC mixed with fly ash based on single factor testing and multifactor orthogonal testing, and proposed the construction technology process and technological measures for use of LCC. Kadela et al. [12] studied the potential of using LCC as the sub-base for pavement structures based on the results of laboratory tests and numerical simulations. Huang et al. [13] proposed use of LCC as subgrade filler to control subgrade settlement in special soil areas by reducing the subgrade weight and consequent stress. Liu et al. [14] established the durability assessment method of LCC subgrade by combining the analytic hierarchy process with fuzzy comprehensive evaluation. Park and Vo [15] examined the resilient modulus of LCC by repeated load triaxial tests, and predicted its fatigue and rutting life when used in subgrade layers. Sychova et al. [16] noted that using LCC as subgrade can improve the durability of subgrade and give the whole subgrade construction higher frost resistance. The above research efforts all indicate that LCC is promising in subgrade construction. For roads using LCC as subgrade filler, the quality of subgrade depends on the quality of LCC. Therefore, the testing and evaluation of LCC quality are supportive of testing and evaluation of subgrade quality.

In field tests, nondestructive testing methods are frequently used to obtain desired properties of the cement-based materials without causing damage [17]. The ultrasound-based method has become an attractive method of field testing of cement-based materials due to its accurate results and high sampling rate [18]. As a nondestructive testing method, the ultrasound-based method has the further characteristics of simple operation, fast detection and cost-effectiveness [19,20]. Demirboğa et al. [21] evaluated the relation between ultrasonic pulse velocity and compressive strength of high-volume mineral-admixtured concrete. Haach et al. [22] utilized ultrasonic testing to characterize the mechanical properties of concretes produced with high early strength cement. Payan et al. [23] discovered that diffuse ultrasound parameters were sensitive to the depth of surface crack in the concrete. Chai et al. [24] developed an algorithm that identified the location of defects in concrete by the attenuation of ultrasonic pulse amplitude. Hamid et al. [25] noticed that there was a good correlation between ultrasonic pulse velocity and the compressive strength of high-performance concrete with silica fume. Gul et al. [26] used ultrasonic pulse velocity to evaluate the compressive strength of mortar with mineral admixtures. The above researches have shown how ultrasonic pulse velocity can be used to evaluate the compressive strength of different concretes. Linear function and exponential function are the primary forms used in evaluation models [27]. For example, Xu et al. [28] found that the compressive strength and ultrasonic pulse velocity in LCC increased linearly with curing time, and proposed use of ultrasonic pulse velocity to quickly evaluate the quality of LCC. Yılmaz et al. [29] examined the effects of water to cement ratio and fines content of the tailings on ultrasonic pulse velocity and on compressive strength of LCC. Liu et al. [30] explored ultrasound propagation in LCC with the help of numerical simulation. Pu et al. [31] attempted to correlate ultrasonic testing results with the material properties of LCC. However, the quantitative relation between ultrasonic testing results and the quality of LCC subgrade is not well understood.

In this paper, LCC was tested by ultrasound technology, aiming to develop an evaluation method for the quality of LCC subgrade. 10 mixture ratios of LCC were designed for the indoor test. Based on the indoor test, the variation rules of ultrasonic pulse velocity and ultrasonic pulse amplitude with age were explored, the quantitative relation between ultrasonic pulse velocity and compressive strength was analyzed, and the effects of the cracking of LCC on ultrasonic pulse velocity and ultrasonic pulse amplitude were observed. Furthermore, the quality of the LCC subgrade was evaluated based on a field ultrasonic test, and the evaluation results were compared with the test results of samples taken from the LCC subgrade field test.

2 Materials and methods

The flowchart of the tests in this study is shown in Fig. 1. The tests included two parts: indoor test and field test. In the indoor test, the quantitative relation between ultrasonic testing results and LCC quality was obtained. With the help of this obtained quantitative relation, the quality of LCC subgrade was evaluated based on the results of field ultrasonic test. Core samples of LCC were taken from the subgrade with self-made equipment and then cut into cylindrical samples with a diameter of 100 mm and a length of 100 mm. Finally, the test results of the core samples were compared with the evaluation results of LCC subgrade to verify the feasibility of using ultrasound technology to evaluate the quality of LCC subgrade.

2.1 Sample preparation

The cement used in this study is 42.5R ordinary Portland cement produced from Zhonglian Cement Factory, Nanjing, China. Table 1 shows the physical properties of the cement. The compound foaming agent was a colorless and transparent liquid, which was a combination of pollution-free animal and plant proteins. The pH value of the compound foaming agent was between 7.5 and 9.0 at room temperature. The compound foaming agent and water was mixed at a mass ratio of 1:50, and the density of the prepared foam (pre-foam) was 50 kg/m^3.

In this paper, the author designed ten mixture ratios of LCC samples. The mixture ratios of LCC were labeled from S1 to S10, as shown in Table 2. The water-cement ratio of mixture ratios labeled from S1 to S5 is 0.65, and the water-cement ratio of mixture ratios labeled from S6 to S10 is 0.70. In order to be consistent with the shape of the samples taken from the LCC subgrade by self-made equipment, the LCC samples were prepared as cylindrical samples with a diameter of 100 mm and a length of 100 mm. Then the samples were cured at a temperature of (21 ± 6) °C and a relative humidity of 50% ± 10%. The uniaxial compressive strength of each sample was obtained by utilizing a testing machine with a loading rate of 0.2 kN/s.

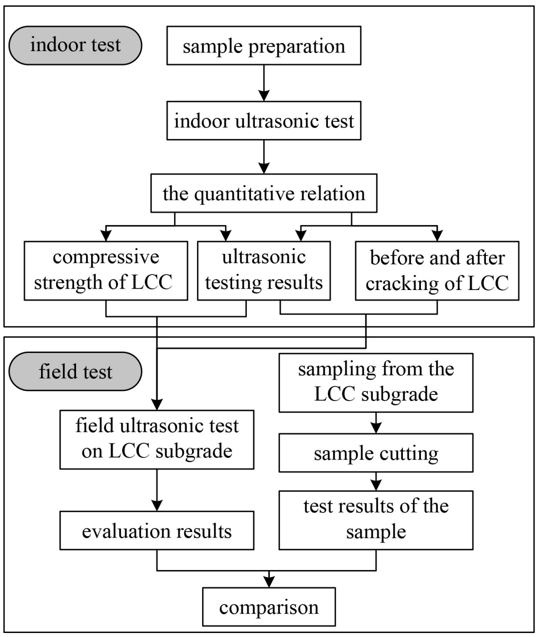

Fig. 1 Flowchart of the test used in this study.

2.2 Indoor test on lightweight cellular concrete samples

In order to study the effects of age, cracking and testing distance on the ultrasonic testing results of LCC, the ultrasonic test was carried out on LCC samples with different conditions of the test.

2.2.1 Indoor ultrasonic test

Figure 2 shows the method for obtaining ultrasonic pulse velocity and ultrasonic pulse amplitude for the LCC sample. The ultrasonic detection instrument used in this study is produced by ZBL SCI & TECH. The ultrasonic pulse amplitude is the amplitude of the first wave crest. The ultrasonic pulse velocity is determined as

$$v_p = \frac{l}{t}, \tag{1}$$

Table 1 Physical properties of the cement

fineness (80 μm, %)	water consumption of normal consistency (%)	initial set (min)	final set (min)	bending strength (MPa)		compressive strength (MPa)	
				3 d	28 d	3 d	28 d
1.2	25.6	165	232	5.2	7.5	28.8	45.3

Table 2 Mixture ratios of LCC

label	cement (kg/m^3)	water (kg/m^3)	pre-foam (L/m^3)
S1	325.0	211.3	683.9
S2	345.0	224.3	664.4
S3	365.0	237.3	645.0
S4	385.0	250.3	624.5
S5	405.0	263.3	606.1
S6	325.0	227.5	667.7
S7	345.0	241.5	647.2
S8	365.0	255.5	626.8
S9	385.0	269.5	606.3
S10	405.0	283.5	585.9

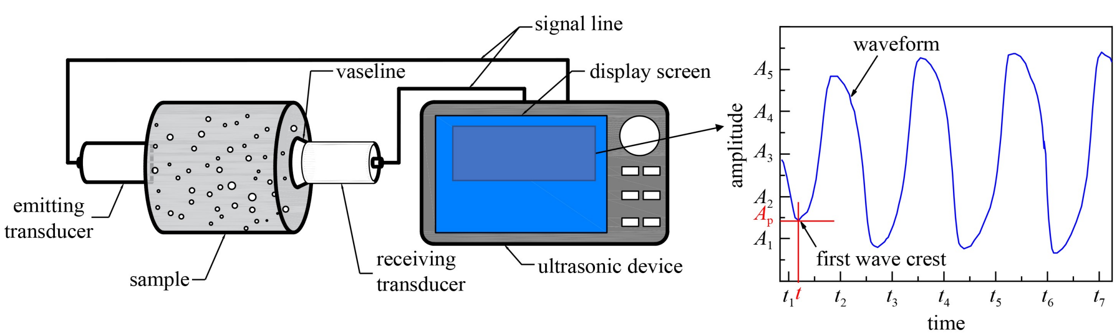

Fig. 2 Indoor ultrasonic testing method.

where l is the testing distance which is the distance between the two transducers, t is the elapsed time from the signal sent by the emitting transducer to the first wave crest received by the receiving transducer.

In the indoor test, the output peak voltage of the ultrasonic detection instrument was 500 V and the frequency of the transducers was 50 kHz. Vaseline was used as the coupling agent to eliminate air between the surface of the sample and the transducers.

2.2.2 Test on LCC samples of different ages

With the increase of age, the hydration products of cement in LCC increase, and the pore structure of LCC becomes denser. The ultrasonic testing results are mainly determined by the material and structure of the tested object. Therefore, the changes in chemical composition and structure of LCC can lead to the changes in ultrasonic testing results.

To observe the effects of the age of LCC on ultrasonic testing results, the ultrasonic test was carried out on the samples at day 3, day 7, day 14, day 21, day 28, day 35, etc. When the ultrasonic testing results of LCC samples were stabilized, the ultrasonic test was stopped and the compressive strength of each LCC sample was obtained by uniaxial compression tests.

2.2.3 Test on cracked samples

As Fig. 3 shows, when ultrasonic waves propagate in the sample, defects such as cracks and voids could cause the ultrasonic waves to be refracted and diffracted, resulting in changes in the first wave received by the receiving transducer. Therefore, the existence of cracks has an influence on the ultrasonic testing results.

When LCC samples were compressed in the uniaxial compression test, cracks appeared on the surface of some samples. The ultrasonic test was carried out on these cracked samples again to observe the effects of cracking of LCC on ultrasonic testing results.

2.2.4 Test on LCC samples with different testing distances

To observe the relation between ultrasonic testing results and testing distance, LCC samples with lengths of 100, 200 and 300 mm were additionally prepared in accordance with the mixture ratio labeled as S3. The ultrasonic test was carried out on these additionally prepared LCC samples, thereby obtaining the ultrasonic testing results of LCC samples with different testing distances.

2.3 Field test on LCC subgrade

After obtaining the quantitative relation between the ultrasonic testing results and LCC quality, the field ultrasonic test was carried out on LCC subgrade, and the quality of LCC subgrade was evaluated based on the obtained quantitative relation. The mixture ratio of LCC subgrade was the mixture ratio labeled as S3 in Table 2. The thickness of the LCC subgrade was 1200 mm. Meanwhile, LCC samples were taken from the subgrade with self-made equipment. Then the test results of these samples were compared with the evaluation results of LCC subgrade.

2.3.1 Field ultrasonic test

When the ultrasonic test is carried out on LCC subgrade, it is necessary to arrange the acoustic pipes vertically in the LCC subgrade, and radial transducers are used for the testing, as shown in Fig. 4. The non-parallelism between the acoustic pipes should not be greater than 1%, and the bottom of the acoustic pipes should be sealed. The diameter of the acoustic pipe used in this study was 50 mm. Before ultrasonic testing, the acoustic pipes were filled with clear water. When the age of the LCC subgrade was day 28, ultrasonic test was carried out at 200, 400, 600, 800 and 1000 mm of the subgrade height.

Since the testing distance in the field test was greater than the testing distance in the indoor test, the peak output voltage of the ultrasonic detection instrument was increased to 1000 V. The frequency of the transducers in the field test was the same as the frequency of the transducers in the indoor test.

2.3.2 Test on LCC subgrade with different testing distances

In field testing, the efficiency of ultrasonic testing is positively correlated with the range of ultrasonic testing.

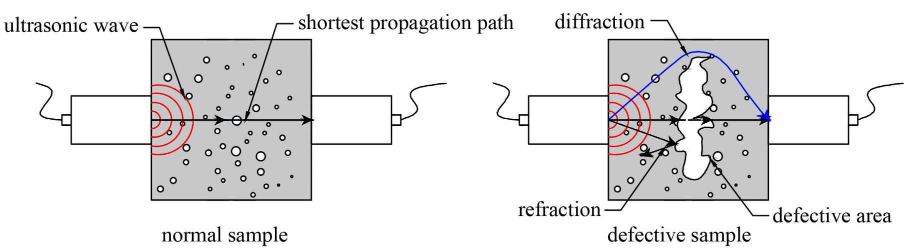

Fig. 3 Propagation path of the ultrasonic wave.

In order to improve the range of ultrasonic testing, the testing distance should be as long as possible. However, with the increase of testing distance, the accuracy of the ultrasonic testing results decrease. It is necessary to determine an appropriate testing distance to ensure the efficiency and accuracy of ultrasonic testing. In the indoor ultrasonic testing, the testing distance was from 100 to 300 mm. Therefore, acoustic pipes spacing from 400 to 1000 mm were arranged in the LCC subgrade, as shown in Fig. 5.

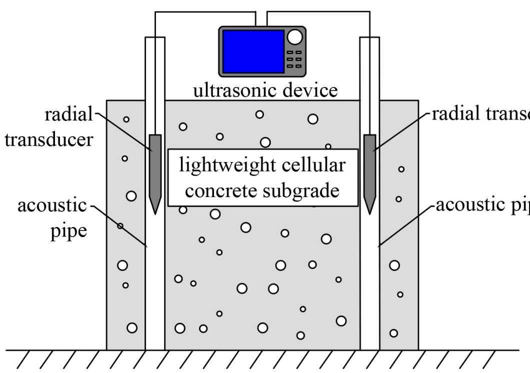

Fig. 4 Field ultrasonic testing method.

2.3.3 Sampling from the LCC subgrade

To verify the feasibility of using ultrasound technology to evaluate the quality of LCC subgrade, the evaluation results of LCC subgrade were compared with the test results of LCC samples taken from the subgrade. With the help of self-made equipment, core samples with a diameter of 100 mm were taken from the LCC subgrade, as shown in Fig. 6. The core samples were visually inspected first to observe whether there were cracks on their surfaces. If there were cracks on the surface then it was considered that the LCC subgrade was 'cracked'. Then each core sample was cut into 5 cylindrical samples with a diameter of 100 mm and a length of 100 mm. Sample H200 meant that the cylindrical sample was cut at 200 mm above the lower surface of the sample. The ultrasonic test was carried out on the cylindrical samples to evaluate whether there were cracks within them. If there were such cracks then it was also considered that

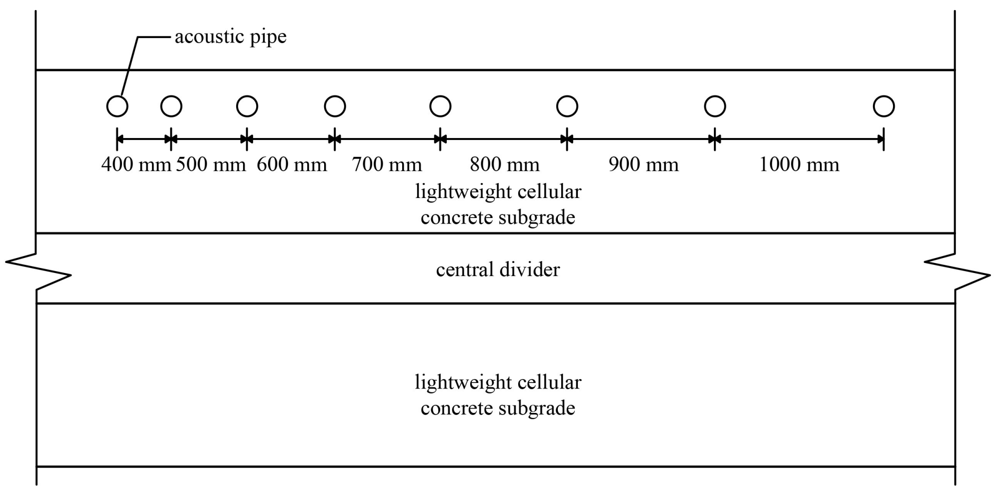

Fig. 5 Arrangement of acoustic pipes for subgrade.

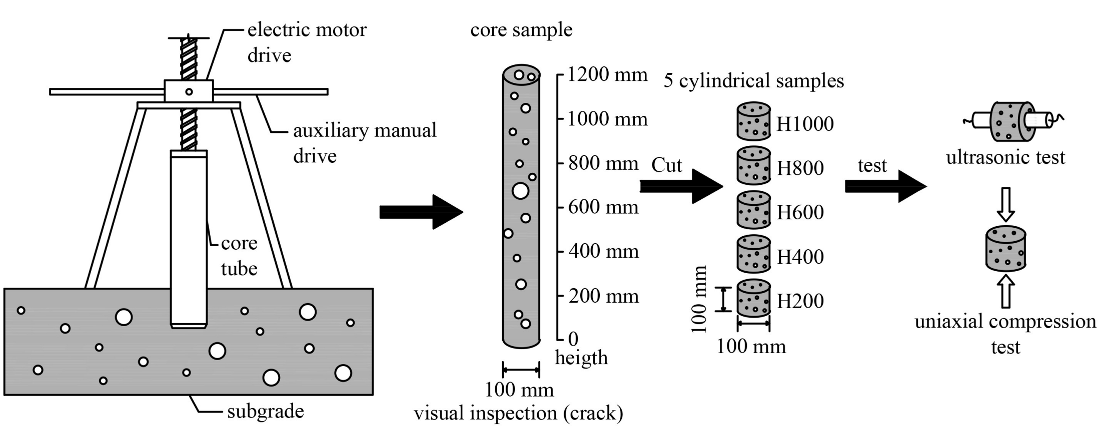

Fig. 6 Flowchart of sampling and testing.

the LCC subgrade was 'cracked'. Finally, the compressive strength of the cylindrical samples was obtained by uniaxial compression testing. The compressive strength of these cylindrical samples could be regarded as the compressive strength of the LCC subgrade.

When taking core samples from the subgrade, the sampling location was randomly selected between every two adjacent acoustic pipes, as shown in Fig. 7.

3 Results and discussion

3.1 Results of age test

The test results shown in Fig. 8 indicate that there is a positive correlation between ultrasonic pulse velocity and age of LCC. From day 3 to day 42 of age, the average increase in ultrasonic pulse velocity is 0.198 km/s. From day 3 to day 14 of age, the increase rate of ultrasonic pulse velocity is the greatest, and the average increase rate from day 3 to day 14 is 0.013 $km \cdot s^{-1} \cdot d^{-1}$. After day 14 of age, the increase rate of ultrasonic pulse velocity decreases, and the average increase rate from day 14 to day 28 of age is 0.003 $km \cdot s^{-1} \cdot d^{-1}$. After day 28 of age, the ultrasonic pulse velocity stabilizes, and the average increase rate from day 28 to day 42 of age is less than 0.001 $km \cdot s^{-1} \cdot d^{-1}$. In addition, it can be noticed from Fig. 8 that when the water−cement ratio and age are the same, the ultrasonic pulse velocity is positively correlated with the cement content of mixture ratio. The cement content is the same for the mixture ratios labeled as S1 and S6, but the ultrasonic pulse velocity of the mixture ratio labeled as S1 is higher than the ultrasonic pulse velocity of the mixture ratio labeled as S6. Meanwhile, the ultrasonic pulse velocity values of mixture ratios labeled from S7 to S10 are also lower than the ultrasonic pulse velocity values of the mixture ratios labeled from S2 to S5. LCC can be considered as a two-phase material including a solid phase (cement matrix) and gaseous phase (pores). The pre-foam content has an influence on the pore volume of LCC sample, and the water-cement ratio has an influence on the density of cement matrix in LCC samples. The ultrasonic pulse velocity is related to the material properties and structure of the tested object. Therefore, the water−cement ratio and pre-foam content also have an influence on the ultrasonic pulse velocity of LCC.

Figure 9 shows that the ultrasonic pulse amplitude first increases with age and then stabilizes. From day 3 to day 42 of age, the average increase in ultrasonic pulse amplitude is 4.35 dB. From day 3 to day 7 of age, the increase rate of ultrasonic pulse amplitude is the greatest, and the average increase rate is 0.46 dB/d. From day 7 to day 35 of age, the increase rate of ultrasonic pulse amplitude decreases, and the average increase rate is 0.09 dB/d. The ultrasonic pulse amplitude values at the day 35 and day 42 of age is approximately the same, and the average increase rate from day 35 to day 42 is less than 0.01 dB/d, indicating that the ultrasonic pulse amplitude of LCC samples has stabilized at day 42 of age. Although the ultrasonic pulse velocity is related to

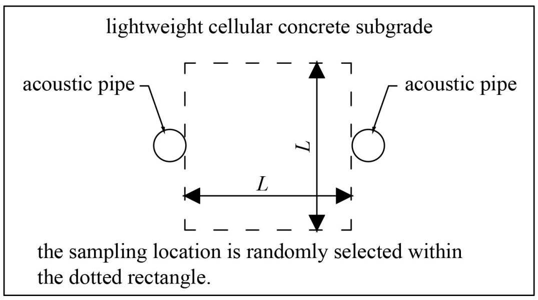

Fig. 7 Sampling location of LCC subgrade (L is the distance between the adjacent acoustic pipes).

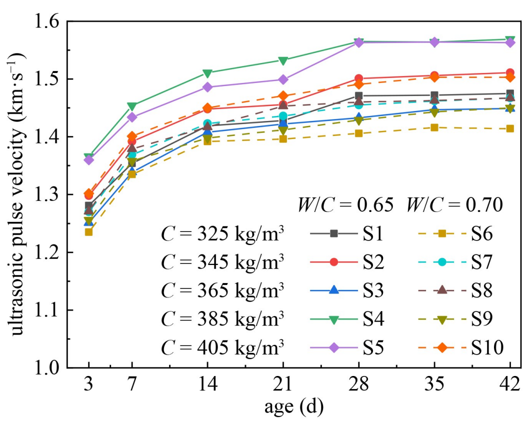

Fig. 8 Relation between ultrasonic pulse velocity and age (S1 to S10 represent the label of LCC mixture ratios, W/C is the water−cement ratio of the mixture ratio, C is the cement content of the mixture ratio).

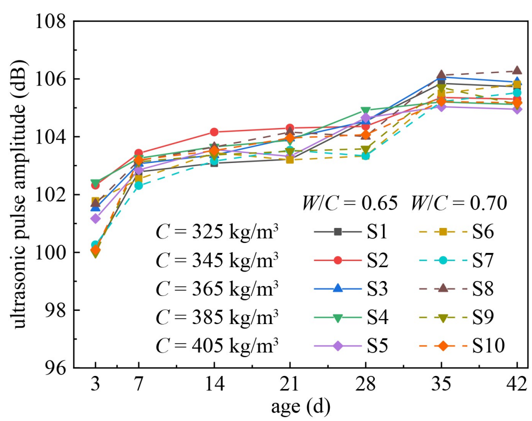

Fig. 9 Relation between ultrasonic pulse amplitude and age (S1 to S10 represent the label of LCC mixture ratios, W/C is the water−cement ratio of the mixture ratio, C is the cement content of the mixture ratio).

the mixture ratio, there is no obvious relation between ultrasonic pulse amplitude and mixture ratio in Fig. 9. When the ultrasonic pulse amplitude is stable, it fluctuates between 104.95 and 106.27 dB.

Figure 10 shows the compressive strength of LCC samples with different mixture ratios at day 3, day 7, day 28 and day 42 of age. From day 3 to day 42 of age, the average increase in compressive strength is 0.590 MPa. From day 3 to day 28 of age, the compressive strength of LCC samples increases, and the average increase rate is 0.022 MPa/d. The compressive strength values at day 28 and day 42 of age are approximately the same, and the average increase rate from day 28 to day 42 is less than 0.002 MPa/d. It can be seen from Fig. 10 that there is a positive correlation between compressive strength and cement content.

It can be noticed from the analysis of the test results that ultrasonic pulse velocity and compressive strength are related to the cement content and age of LCC. Therefore, it is feasible to obtain the compressive strength of LCC with the help of the nondestructive ultrasound-based method.

3.2 Evaluation for compressive strength

According to the results of the ultrasonic test and uniaxial compression test, the compressive strength of LCC samples is positively correlated with the ultrasonic pulse velocity. The commonly used fitting formulas for compressive strength are linear function and exponential function. The compressive strength curves of ultrasonic pulse velocity are shown in Fig. 11. However, it can be seen that the goodness of fit of the fitting formulas (f_{c1} and f_{c2}) is not satisfying ($R^2 < 0.9$).

The compressive strength of LCC obtained by mechanical test is accurate to 0.1 MPa in subgrade construction. If the error between the compressive strength obtained by mechanical test and the compressive strength evaluated based on ultrasonic pulse velocity is less than 0.05 MPa; the error can be considered as zero after rounding. Therefore, in some cases, the relative error between the compressive strength obtained by mechanical test and the compressive strength evaluated based on ultrasonic pulse velocity is allowed to be significant. For example, when the compressive strength obtained by mechanical test is 1.0 MPa, any relative error is acceptable as long as it is less than 5%. In this case, it may not be accurate enough to evaluate the goodness of fit of the fitting formulas (f_{c1} and f_{c2}) by R^2. Therefore, a probability distribution is introduced to evaluate the goodness of fit. If the errors are subject to the normal distribution, and the absolute value of the errors is less than 0.05 MPa with a 95% probability, it can be considered that the compressive strength evaluated based on ultrasonic pulse velocity is in a good agreement with

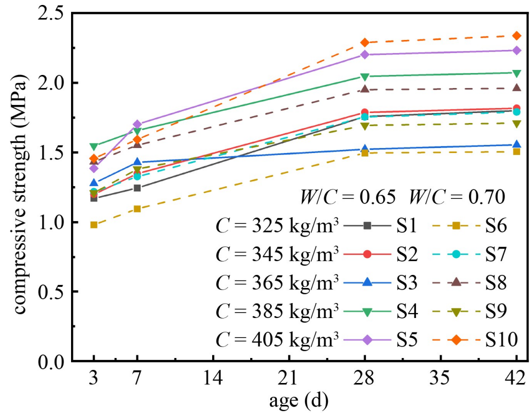

Fig. 10 Relation between compressive strength and age (S1 to S10 represent the label of LCC mixture ratios, W/C is the water−cement ratio of the mixture ratio, C is the cement content of the mixture ratio).

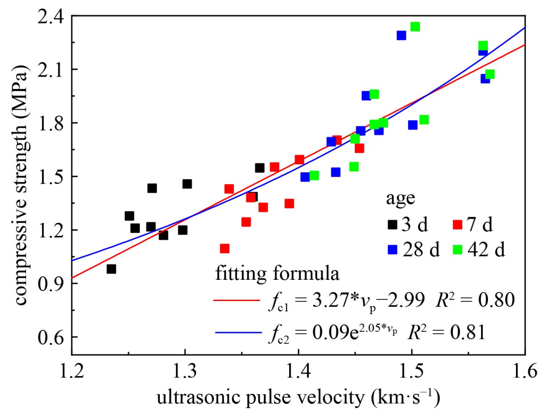

Fig. 11 Compressive strength curves of ultrasonic pulse velocity (f_c is the compressive strength, v_p is the ultrasonic pulse velocity).

the compressive strength obtained by mechanical test, which means that the goodness of fit of the fitting formula is satisfying.

Random variables $(x_1,x_2,\ldots,x_n)$ represent the errors between the compressive strength obtained by mechanical test and the compressive strength evaluated based on ultrasonic pulse velocity. If random variables $(x_1,x_2,\ldots,x_n)$ are subject to the normal distribution, the confidence interval for $(x_1,x_2,\ldots,x_n)$ is determined as

$$\bar{x}-\frac{t_{\alpha/2,(n-1)}s}{\sqrt{n}}\leqslant\mu\leqslant\bar{x}+\frac{t_{\alpha/2,(n-1)}s}{\sqrt{n}}, \tag{2}$$

where μ is the confidence interval for $(x_1,x_2,\ldots,x_n)$, $\bar{x}$ is the sample mean, n is the sample capacity, s is the sample standard deviation, $t_{\alpha/2,(n-1)}$ is the factor for the T-distribution with $n-1$ degrees of freedom for a range of two-sided critical regions and a confidence level of $1-\alpha$. In this study, n is 40, α is 0.05 and $t_{\alpha/2,(n-1)}$ is 2.0227.

The errors between the compressive strength obtained by mechanical test and compressive strength evaluated by fitting formulas (f_{c1} and f_{c2}) were calculated, and two groups of errors were obtained, each containing 40 error values. Kolmogorov−Smirnov test is used to judge whether a group of data is subject to a certain distribution (Poisson distribution, normal distribution, lognormal distribution, etc.). The two groups of errors are subject to the normal distribution according to the Kolmogorov−Smirnov test results. The mean and standard deviation of each group of errors were calculated, and then substituted into Eq. (2) to calculate the confidence interval for each group of errors with a confidence level of 95%. The calculation in this case shows that the confidence interval of the errors between the compressive strength obtained by mechanical test and the compressive strength evaluated by fitting formulas f_{c1} is $-0.51 \leqslant \mu \leqslant 0.51$, indicating that the goodness of fit of the fitting formula f_{c1} is not satisfying. The confidence interval of the errors between the compressive strength obtained by mechanical test and the compressive strength evaluated by fitting formulas f_{c2} is $-0.49 \leqslant \mu \leqslant 0.49$, indicating that the goodness of fit of the fitting formula f_{c2} is satisfying. Therefore, the fitting formula f_{c2} can be used to evaluate the compressive strength of LCC in this study.

3.3 Test results of cracked sample and samples with different testing distances

When LCC samples were compressed in the uniaxial compression test, cracks appeared on the surface of some samples. The width of these cracks ranges from 0.1 to 2.4 mm. In the uniaxial compression test, there are 32 complete samples with cracks on the surface, while some samples seriously damaged and some samples have no cracks on the sample surface. The ultrasonic pulse velocity before and after cracking of LCC samples is shown in Fig. 12. The test results show that after the samples are cracked, the ultrasonic pulse velocity decreases. It is found from the statistical data that the ultrasonic pulse velocity decreases by 34.43% on average. The minimum percentage of the decrease in ultrasonic pulse velocity is 2.07%. The maximum percentage of the decrease in ultrasonic pulse velocity is 89.71%. Among the 32 cracked samples, only the ultrasonic pulse velocity of sample No. 21 decreases by less than 5%. This means that after the sample becomes cracked, there is at least a 95% probability that the ultrasonic pulse velocity will decrease by more than 5%.

Figure 13 shows that after the samples become cracked, the ultrasonic pulse amplitude decreases. Moreover, it is

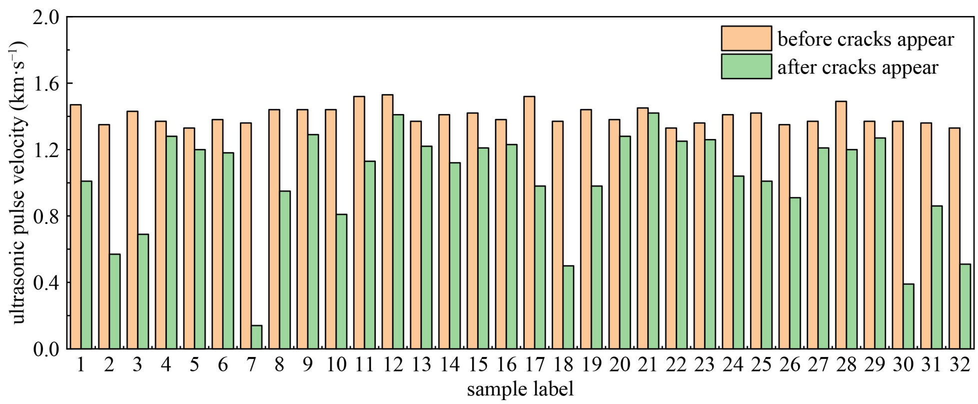

Fig. 12 Ultrasonic pulse velocity before and after cracking of LCC samples.

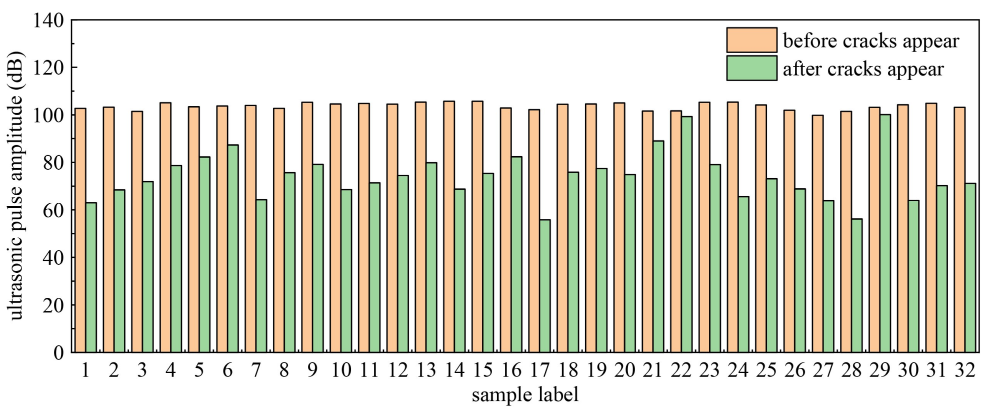

Fig. 13 Ultrasonic pulse amplitude before and after cracking of LCC samples.

found from the statistical data that the ultrasonic pulse amplitude decreases by 31.27% on average. The minimum percentage of decrease in ultrasonic pulse amplitude is 2.42%. The maximum percentage of decrease in ultrasonic pulse amplitude is 45.42%. Among the 32 cracked samples, only the ultrasonic pulse amplitude of sample No. 22 decreases by less than 10%. This means that after the sample is cracked, there is at least a 95% probability that the ultrasonic pulse amplitude decreases by more than 10%.

Figure 14 shows the ultrasonic testing results of samples with different testing distances. As Fig. 14(a) shows, with the increase of testing distance, the ultrasonic pulse velocity was basically unchanged, indicating that there is no obvious relation between ultrasonic pulse velocity and testing distance. As Fig. 14(b) shows, with the increase of testing distance, the ultrasonic pulse amplitude decreases. This is because the energy attenuation of the ultrasonic wave in the propagation increases with the propagation distance. When the testing distance increases by 100 mm, the average value of ultrasonic pulse amplitude decreases by 1.33 dB.

The ultrasonic testing results of cracked samples show that the existence of cracks can cause a decrease in ultrasonic pulse velocity and ultrasonic pulse amplitude of LCC. According to the above quantitative relation, whether there are cracks in LCC can be evaluated by the ultrasound-based method.

3.4 Field ultrasonic testing results of LCC subgrade

The ultrasonic testing results of the LCC subgrade with different testing distance is shown in Fig. 15. As Fig. 15(a) shows, there is no obvious relation between ultrasonic pulse velocity and testing distance, and the value of ultrasonic pulse velocity fluctuates between 1.322 and 1.407 km/s. Figure 15(b) shows that the ultrasonic pulse amplitude is negatively correlated with the testing distance. When the testing distance is 400 mm, the average value of ultrasonic pulse amplitude is 103.81 dB. When the testing distance is 1000 mm, the average value of ultrasonic pulse amplitude is 94.40 dB. When the testing distance increases by 100 mm, the average value of ultrasonic pulse amplitude decreases by 1.57 dB, which is slightly larger than the decrease in ultrasonic pulse amplitude in the indoor test. It is also

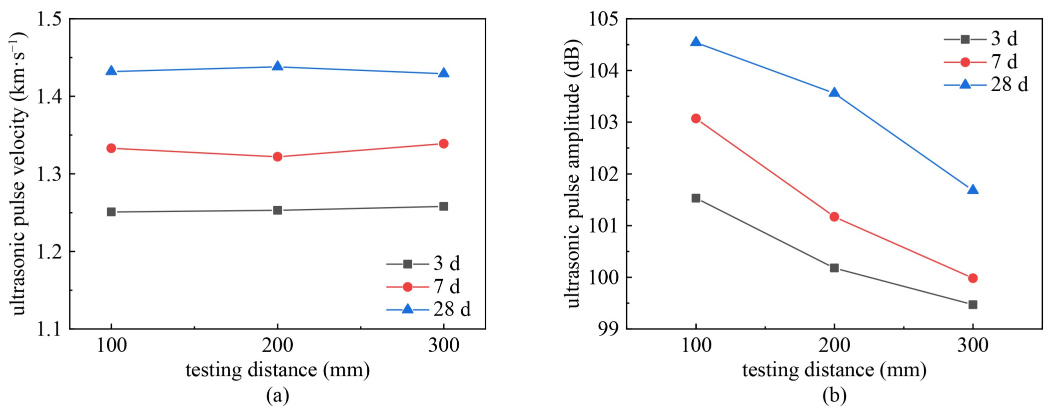

Fig. 14 (a) Relation between ultrasonic pulse velocity and testing distance and (b) relation between ultrasonic pulse amplitude and testing distance (indoor test).

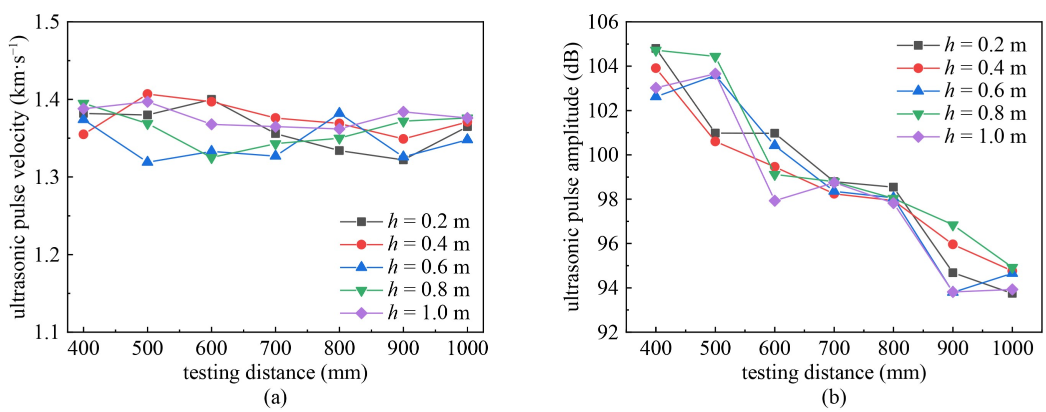

Fig. 15 (a) Relation between ultrasonic pulse velocity and testing distance and (b) relation between ultrasonic pulse amplitude and testing distance (field test, h is the height of the LCC subgrade).

found that there is no obvious relation between ultrasonic testing results and the height of the LCC subgrade, which means that the LCC is uniform in the vertical direction.

According to the ultrasonic signal received by the ultrasonic detection instrument in the testing, it can be noted that the ultrasonic signal is stable when the testing distance is from 400 to 600 mm, the ultrasonic signal is relatively stable when the testing distance is 700 and 800 mm, and the ultrasonic signal is unstable when the testing distance is 900 and 1000 mm. Figure 16 shows the volatility of ultrasonic testing results when five ultrasonic tests are continuously carried out. It is found that with the increase of testing distance, the volatility of ultrasonic testing results increases. When the testing distance is greater than 800 mm, the volatility increases significantly. The efficiency of ultrasonic testing is positively correlated with the range of ultrasonic testing. The longer the testing distance, the wider the range of ultrasonic testing. However, with the increase of testing distance, the volatility of ultrasonic testing results increases, resulting in a decrease in the accuracy of ultrasonic testing. Based on the field test results, 800 mm is recommended to be used for the field ultrasonic testing.

3.5 Quality evaluation of LCC subgrade based on ultrasonic testing results

The compressive strength of the LCC subgrade is designed to be greater than 1.2 MPa. Based on the fitting formula f_{c2}, it can be evaluated that when the ultrasonic pulse velocity is greater than 1.264 km/s, there is a 95% probability that the compressive strength is greater than 1.2 MPa. Meanwhile, after the LCC sample becomes cracked in the indoor test, there is at least a 95% probability that ultrasonic pulse velocity decreases by more than 5% and ultrasonic pulse amplitude decreases by more than 10%. The cracks in LCC subgrade are generally wider, longer and more complex than the induced cracks in LCC sample. It is reasonable to believe that when LCC subgrade has become cracked, the decrease in ultrasonic pulse velocity and ultrasonic pulse amplitude is greater. Therefore, if the minimum value of ultrasonic pulse velocity is greater than 95% of the average value of ultrasonic pulse velocity and the minimum value of ultrasonic pulse amplitude is greater than 90% of the average value of ultrasonic pulse amplitude, it could be considered that there is no crack in the LCC subgrade.

Figure 17(a) shows that all the ultrasonic pulse velocity values are greater than 1.264 km/s, which means the compressive strength of the LCC subgrade is considered suitable for purpose based on the ultrasonic testing results. Meanwhile, all the ultrasonic pulse velocity values are greater than 95% of the average value of ultrasonic pulse velocity, and all the ultrasonic pulse amplitude values are greater than 90% of the average value of ultrasonic pulse amplitude, as shown in Fig. 17. Thus, it is considered that there is no crack in the LCC subgrade. According to the above evaluation results, the quality of the LCC subgrade is considered suitable for purpose.

3.6 Test results of the samples taken from the LCC subgrade

When the age of the LCC subgrade was day 28, 5 core samples were taken between every two adjacent acoustic pipes in the subgrade, and a total of 35 core samples were taken. Based on the results of visual inspection, there were no cracks on the surfaces of the core samples. Each core sample was cut into 5 cylindrical samples. However, some samples were unsuitable in terms of size and some samples were broken during the cutting. Unsuitable cylindrical samples were rejected and 115 cylindrical samples were obtained. The ultrasonic testing results of these cylindrical samples show that the minimum value of ultrasonic pulse velocity is greater than 95% of the average value of ultrasonic pulse velocity, and the

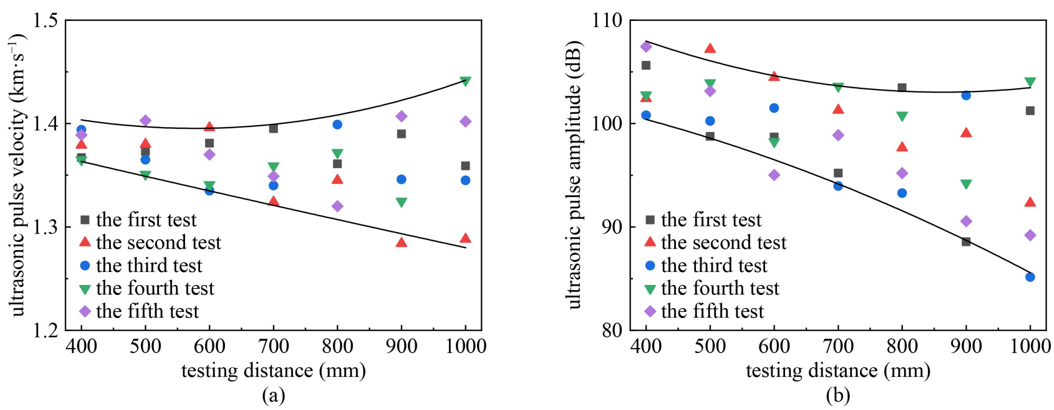

Fig. 16 Volatility of (a) ultrasonic pulse velocity and (b) ultrasonic pulse amplitude at different testing distances. (Ultrasonic tests were carried out at the subgrade height of 600 mm.)

minimum value of ultrasonic pulse amplitude is greater than 90% of the average value of ultrasonic pulse amplitude. Therefore, it is considered that there is no crack in the cylindrical samples. Figure 18(a) shows that the compressive strength values of these cylindrical samples are between 1.2 and 1.6 MPa, which means the compressive strength of the LCC subgrade is suitable for purpose. It is found from Fig. 18(b) that the errors between the experimental data and the evaluation results based on ultrasonic pulse velocity are mostly less than 0.05 MPa. Among the 115 cylindrical samples, only 5 cylindrical samples have an error greater than 0.05 MPa, so the accuracy of the compressive strength evaluated by the fitting formula f_{c2} is satisfying.

According to the above test results of the samples taken from the LCC subgrade, the quality of the LCC subgrade is suitable for purpose, which is consistent with the evaluation results based on the ultrasonic testing results.

4 Conclusions

In this study, the quantitative relation between ultrasonic testing results and LCC quality was observed, and a quality evaluation method for LCC subgrade was proposed. The quality of LCC subgrade was evaluated with respect to compressive strength and crack discrimination. The main conclusions are as follows.

1) The compressive strength of LCC samples is positively correlated with ultrasonic pulse velocity. A fitting formula of compressive strength based on ultrasonic pulse velocity is given, and the absolute value of the error between the strength evaluated based on fitting formula and the strength obtained by mechanical test is less than 0.05 MPa with a probability of 95%.

2) The indoor test results show that after the LCC sample has become cracked, there is at least a 95% probability that ultrasonic pulse velocity decreases by more than 5% and ultrasonic pulse amplitude decreases by more than 10%. Based on the above quantitative relation, whether the LCC is cracked can be evaluated by the ultrasound-based method.

3) The efficiency of ultrasonic testing is positively correlated with the range of ultrasonic testing. The longer the testing distance, the wider the range of ultrasonic testing. However, with the increase of testing distance, the volatility of ultrasonic testing results increases, resulting in a decrease in the accuracy of ultrasonic

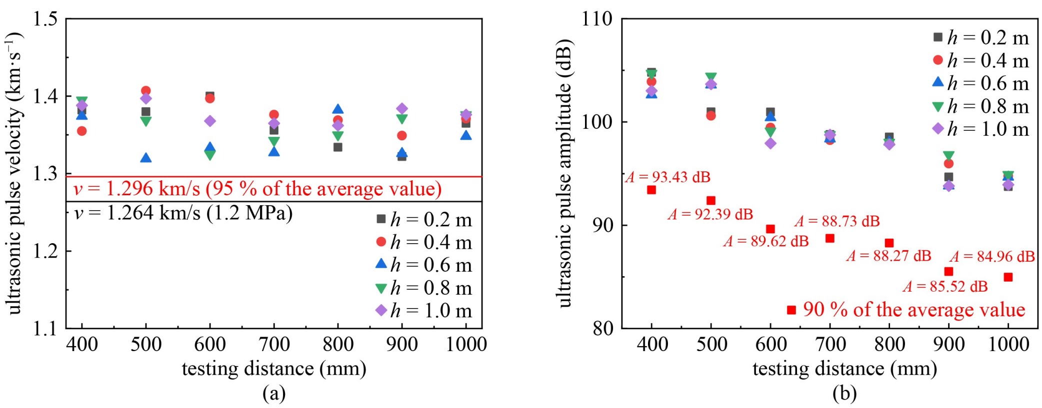

Fig. 17 Quality evaluation of LCC subgrade based on (a) ultrasonic pulse velocity and (b) ultrasonic pulse amplitude. (v is the ultrasonic pulse velocity and A is the ultrasonic pulse amplitude.)

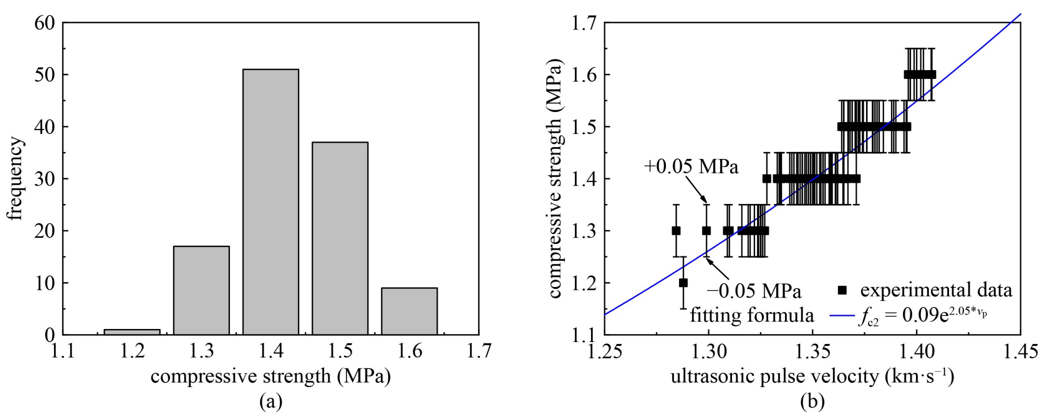

Fig. 18 (a) Experimental data and (b) evaluation results of compressive strength of the samples taken from the LCC subgrade.

testing. Based on the field test results, 800 mm is recommended to be used for the field ultrasonic testing to maintain efficiency and accuracy.

4) According to the evaluation results based on ultrasonic testing results and test results of the samples taken from the LCC subgrade, the quality of the LCC subgrade is suitable for purpose. The evaluation results are consistent with the test results, which proves that it is feasible to evaluate the quality of LCC by the nondestructive ultrasound-based method.

Acknowledgements This study was funded by the National Natural Science Foundation of China (Grant No. 51609071), the Fundamental Research Funds for the Central Universities (Nos. B200202087, B200204032).

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