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Study on water damage mechanism of asphalt pavement based on industrial CT technology

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Abstract

It is impossible to study the relationship between water damage and voidage of asphalt pavement because the voidage of pavement core sample cannot be determined accurately. Based on the industrial computed tomography (CT) scanning technology for core samples of real void fraction measurement, dynamic water flushing apparatus to water damage damage of core samples, the CT scan void fraction and destruction after the relationship between splitting strength and CPN rutting depth of core samples, respectively, set up different lanes of void fraction and cleavage strength and the fitting formula of rut depth.

Keywords: asphalt pavement, industrial CT, voidage, water damage

1 Introduction

As early as 1960s, foreign countries have begun to carry out the research on the water damage mechanism of asphalt pavement. However, due to the extremely complex factors affecting the water damage of asphalt pavement, many problems have not yet been solved completely [1–3]. Shen Jin'an [4] effectively reduced water damage by increasing compaction work and reducing voidage; Zhang yuan et al. [5, 6] used GPR technology to evaluate the water damage of asphalt pavement; Gao Yang et al. [7, 8] studied the damage mechanism of asphalt pavement considering the influence of hydrodynamic pressure. At present, the evaluation methods of water damage performance of asphalt pavement can be divided into 2 categories: one is based on asphalt mixture, that

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is, to evaluate the index of loose asphalt mixture after water damage. However, the disadvantage of this method is that it cannot simulate the real state of asphalt pavement during operation, and can only analyse the water damage between asphalt and stone. The other is based on the index evaluation of asphalt mixture samples or core samples damaged by water. A number of domestic scholars pointed out that the void fraction of asphalt mixture is one of the leading causes of asphalt pavement water damage, and sufficient compaction can reduce the connectivity of voids, thus reducing the possibility of asphalt pavement water damage. There are significant errors in the core voidage measurement [9]. On the one hand, the surface dry method is adopted to measure the volume density of the core sample, and the results are directly related to the operators' techniques, and the results obtained by different testers are greatly different. On the other hand, there is substantial error in the maximum theoretical density of the mixture, and the gradation of the core samples is not consistent. However, the same maximum theoretical density is adopted, and there is an obvious deviation. However, for the current void fraction calculation system, there are still some difficulties in accurately measuring the void fraction of specimens or core samples, which has led to the inability to accurately analyse the relationship between the void fraction of asphalt pavement and water damage.

2 Test method of void fraction based on industrial CT scanning technology

2.1 Industrial CT scanning

The results show that the compaction and void fraction of indoor Proctor compaction specimens are not consistent with the real asphalt pavement. Therefore, to study the water damage mechanism of asphalt pavement, this paper selects asphalt pavement core as research samples. Relevant research shows that [10, 11] due to the segregation of asphalt pavement in the construction process, there will be 30% calculation error according to the current void fraction calculation system. At the same time, when the asphalt pavement is in operation, the composition and structure of the mixture will change slightly, which will further affect the accuracy of void fraction calculation. To accurately calculate the void fraction of the asphalt pavement core sample, this paper uses industrial CT technology.

Fig. 1 Industrial CT scanning system.

Industrial CT is a nuclear imaging technology used in industry, the basic principle of which is based on the weakening and absorption characteristics of radiation in the detected object [12, 13]. It includes the following basic components: radiation source, radiation detector and collimator (Figure 1). The industrial CT technology is used to scan and detect the asphalt pavement core samples. The background, voids, asphalt mortar and aggregate are gradually separated by 3 Otsu methods. The specific process is shown in Figure 2.

2.2 Determination of voids in core samples

Only one section void fraction index can be obtained by scanning asphalt pavement core samples with industrial CT. To study the distribution of the void fraction of the core sample, the void fraction of the core sample with depth is extracted, as shown in Figure 3.

Fig. 2 Image segmentation by OSTU method with the circular block (5 loops).

Fig. 3 Void fraction distribution of pavement core sample.

Based on Figure 3, the maximum void fraction of the core sample appears at the top of the specimen. With the increase in depth, the void fraction of the face decreases, and the minimum value appears at 2/3 of the depth, while the void fraction of the back increases gradually. Under the influence of the end effect, the void fraction at both ends of the specimen is larger. The gap and its distribution in this position are not necessarily representative. Therefore, the upper and lower data should be excluded before analysis. In the calculation of asphalt pavement core sample void fraction, the main problem is how to convert the section void fraction into a three-dimensional void fraction, in which the determination of the number of section images is a crucial step.

How to determine the number of section images, that is, how to extract the number of section images, can make the sample mean value approach to the overall mean μ under the required guarantee rate, which is a problem of sample size. According to the related studies [14, 15], when 32 cross-sections are taken, the void fraction error of $\pm 0.25\%$ can be met at a 95% guarantee rate. Further, to increase the accuracy of core sample void fraction detection, this paper performs a section scan every 0.1 mm with the depth of the core sample, and the number of scans for each core sample varies according to the thickness, which is controlled at 300–500 times to improve the accuracy of core sample void fraction scanning.

2.3 Void fraction analysis of different lanes

In this paper, the core is taken from the roadway and shoulder area, and the industrial CT is used to scan and calculate the void fraction, and the void fraction is sorted into a map. The results are shown in Figure 4.

According to Figure 4, in the small void fraction region, the lane and shoulder core-like void fraction are almost identical. However, at void fraction greater than 3%, the overall travel lane core sample void fraction is

Fig. 4 Core CT scan void fraction.

smaller than the shoulder core sample void fraction, and this difference increases as the void fraction increases. The maximum value of void fraction was 8.97% for the lane cores and 6.89% for the shoulder cores, a difference of 2.08% in void fraction. Through the analysis, it is found that the reason for this situation is that the shoulder belongs to the edge, which is easy to appear as coarse segregation in the construction process. At the same time, there is no traffic load on the shoulder, and the traffic lane often receives the traffic load so that the secondary compaction effect will appear in the operation process. Hence, the void fraction of the overall core sample is small. By observing the distribution of void fraction in shoulder core samples, it is found that there are gentle curve points in the void fraction range of 4%–5%, whereas the curve slope is larger when the void fraction is less than 4% or more than 5%. This result shows that there are many void fraction values in the range of 4%–5%, and the interval value is directly corresponding to the void fraction of asphalt mixture design. For the same lane core samples, the void fraction distribution also has the same trend, but its gentle range is 3.5%–4.5%, and the slope decreases in the area greater than 4.5%. The main reason for this result is that under the action of traffic load, the void fraction of carriageway falls as a whole and then forms the downward movement of gentle interval. At the same time, in the area larger than the gentle section, the slope of the curve decreases, which is basically consistent with that of the gentle section, which further indicates the secondary compaction effect of the carriageway.

At the same time, routine void fraction tests were carried out for each core sample to compare the differences between them. The results are shown in Figure 5.

Fig. 5 Comparison of void fraction results of core samples.

Based on Figure 5, it can be found that the overall trend of void fraction measured by CT scanning is consistent with that measured by the test method, but there are great differences in most of the core samples. Among them, the core sample with the small void fraction is obviously different from that with the large void

fraction. The maximum error of void fraction measured by test method is 73.5%, and that of the core sample is 2.02%. The analysis found that the main reason for this result is that both, whether the void fraction is small or large, indicate the presence of segregation of asphalt pavement. The void fraction measured by the test method is based on the premise of uniform formation of asphalt mixture, but when the phenomenon of asphalt pavement segregation, the test method measured void fraction will be in error. Also, for determining void fraction, the core sample is saturated with water and then wiped dry with a towel, which leads to errors. Even if the same core sample is operated twice by the same tester, the results may be different. Related researchers have shown^[10] that the error due to segregation will increase accordingly with the increase in the severity of segregation, and the error can reach up to 30%. However, larger errors also exist in the target void fraction interval of 4%–5%. The interval does not belong to the segregation interval, so there is no error caused by segregation; the analysis is mainly due to the test operation saturation surface dry condition error. At the same time, during the operation of asphalt pavement, the phenomenon of aggregate spalling occurs due to wheel load, which leads to variations in asphalt pavement grading. The maximum theoretical density also varies, that is, there will be errors in the void fraction measured by the test method.

3 Study of void fraction based on splitting strength and water damage trends

3.1 Dynamic water flushing device

To analyse the influence of void fraction on the water damage resistance of asphalt pavement, it is necessary to carry out water damage to the core sample of asphalt pavement. By evaluating the performance of the core sample after damage, the ability of asphalt pavement to resist water-destroyed damage is analysed. Conventionally, a hydrostatic pressure method of water damage to asphalt pavements is used. The presence of closed voids prevents water from entering all the voids, while the hydrostatic head pressure method to simulate dynamic water pressure does not correspond to the actual pavement condition [16, 17]. To be closer to the actual situation of asphalt pavement water damage, this paper adopts the dynamic water flushing instrument for asphalt pavement core samples for water damage destruction. The pressure range is -0.095–0.7 MPa, that is, 8 s of alternating positive and negative pressure, while the container temperature is selected as the most unfavourable environmental conditions. In this paper, the selected temperature is 60 °C, non-directional erosion 1 h.

3.2 Study of void fraction based on leakage strength and water damage trends

In this paper, to study the correlation between void fraction and water damage trends of asphalt pavement, a kinetic water flushing instrument was used to perform water damage destruction of asphalt pavement core samples and the destroyed core samples were subjected to splitting test. The split test results were mapped and analysed with the core sample CT scan void fraction, and the results are shown in Figure 6.

Take the core sample CT scan void fraction as a horizontal coordinate and leakage strength as a vertical coordinate. Use the power model to fit, the carriageway core sample leakage strength and CT scan void fraction fit formula (1), shoulder core sample leakage strength and CT scan void fraction fit formula (2).

$$\begin{aligned} y &= 2.7515X^{-0.168} \\ R^2 &= 0.5612 \end{aligned} \quad (1)$$

$$\begin{aligned} y &= 2.6113X^{-0.563} \\ R^2 &= 0.7097 \end{aligned} \quad (2)$$

Figure 6 shows that the leakage strength of the core sample of the traffic lane and the road shoulder will increase with the decrease of the void fraction of the core sample CT scan. When the void fraction of the traffic lane core sample is less than 5%, the leakage strength of the core sample increases rapidly; when the void fraction

Fig. 6 Relationship between void fraction and leakage strength in CT scan.

of the road shoulder core sample is less than 7%, the leakage strength increases rapidly. The air remaining in the pores of the water-soaked core sample is compressed during the pressure increase of the dynamic water scourer. As water continues to fill the open pores, coupled with the action of pressure, the water in the open pores will continue to flow. Under the action of this flow, the asphalt mixture surface in the open pore surface area bears normal stress and shear stress, and this flow operation will invade the interface between asphalt and stone. Then it causes a spalling effect. When the pressure released is negative, the water in the open pore will flow out of the pore rapidly, which will form the scouring effect and further affect the adhesion effect between asphalt and stone. At this point, the air in the closed pore will expand continuously, which affects not only the overall structural performance of asphalt mixture core sample but also the bonding effect between asphalt and stone in the closed gap. When the void fraction of the core sample is larger, the damaging effect of dynamic water washing on the core sample is more obvious. However, when the void fraction of the lane core sample is greater than 5% and that of shoulder core sample is greater than 7%, the leakage strength of core sample does not change significantly. The main reason for this issue is that when the void fraction of the core sample exceeds the critical value, the damaging effect of the hydrodynamic wash has been completely generated, which does not change significantly with the void fraction of the core sample.

The reason for this result is that the carriageway is subjected to traffic loading, and there is secondary compaction. The shoulder asphalt pavement is not subjected to traffic loads, and its overall void fraction is larger and, because it is located at the edge, there is less fine aggregate and more coarse aggregate concentration. Besides, the differences in the air contact surface of the asphalt slurry inside the mixture of different lanes also lead to different degrees of ageing, so there is a significant difference in the leakage strength of different lanes.

4 CPN-based void fraction and water damage development trend study

4.1 Rotary loaded wheel tester (CPN)

The CPN is a Rotary Loaded Wheel Tester, which is used to evaluate the rutting of specimens and core samples in both wet and dry conditions and at controlled temperatures [18, 19]. The load is applied by rotating the main wheel and 10 driven rubber wheels on the edge of the main wheel, each of which is configured at 125 N. The contact pressure is calculated to be 0.69 MPa. When the main wheel rotates for one week, the driven rubber wheels are loaded 10 times. Since the load was applied in a rotating manner, the CPN more closely approximated the actual condition of the pavement receiving the wheel load. The evaluation criteria are 16,000 times of operation of the small wheel, the depth of the rutting of the test piece, or the running times of the small wheel when the depth of the wheel rut reaches 6.35 mm. To study the development trend of void fraction and water damage, the wet state (i.e. the water tank is filled with water) and the temperature of 60 鈰儁re selected as the test conditions, and the development trend of water damage under different void fraction values is studied

through the rutting depth of CPN.

4.2 Void fraction and development trend of water damage

Further, to study the relationship between core sample void fraction and water damage trends, rutting tests were conducted on core samples with different void fraction values using CPN equipment to establish the relationship between void fraction and CPN rutting depth as shown in Figure 7.

Fig. 7 Relationship between CT scan void fraction and CPN rutting depth.

The core sample CT scan void fraction as horizontal coordinates, CPN rutting depth as vertical coordinates, using the exponential model for fitting, resulting in the carriageway core sample CPN rutting depth and CT scan void fraction fit formula (3), shoulder core sample CPN rutting depth and CT scan void fraction fit formula (4).

$$y = 1.7097e^{0.1371x} \quad R^2 = 0.6332 \quad (3)$$

$$y = 1.0009e^{0.0833x} \quad R^2 = 0.6604 \quad (4)$$

It can be seen from Figure 7 that the rutting depth of the core CPN increases with the increase of the void fraction in CT scanning, and the increasing trend is constantly rising. The main reason is that under the load of CPN rutting instrument, the mixture is first compacted twice, that is, the mixture migrates to the void. The larger the void fraction is, the more mixture is transferred, that is, the greater the rutting depth. In the same CT scan gap, the carriageway core sample CPN rutting depth is greater than the CPN rutting depth of the shoulder; the analysis is mainly due to the fact that the shoulder is located in the asphalt pavement edge. Asphalt mixture in the paving process often occurs in the edge of the coarse segregation, resulting in the edge of the coarse aggregate concentration, the formation of a strong skeleton, not easy to deform; in the CPN rutting meter loading, shoulder rutting depth is smaller. In the same CT scan gap, the carriageway core sample CPN rutting depth is greater than the CPN rutting depth of the shoulder; the analysis is mainly due to the reason that the shoulder is located in the asphalt pavement edge; asphalt mixture in the paving process often occurs in the edge of the coarse segregation, resulting in the edge of the coarse aggregate concentration, the formation of a strong skeleton, not easy to deform. Under the loading of CPN rutting meter, the rutting depth of the shoulder is small. The rutting depth of lane core sample changes with the change of void fraction, but the rutting depth of shoulder core sample only changes slightly when void fraction changes obviously. After the analysis, it is found that the main reason is the concentration of coarse aggregate and strong skeleton effect.

5 Conclusion

1. By scanning the asphalt pavement core samples with industrial CT, it is found that the void fraction on the top and bottom of the core sample is too large, whereas the void fraction in the middle of the core sample is too small.
2. Due to the secondary compaction effect, the overall shoulder core CT scan void fraction is larger than the lane core CT scan void fraction and the lane core CT scan void fraction has a flat curve in the range of 4%–5%. The shoulder core CT scan void fraction has a flat curve in the 3.5%–4.5% range, with a concentration effect. A flat curve in the 3.5%–4.5% range has a concentration effect.
3. Due to the factors such as segregation, the variation of asphalt pavement gradation during operation period and operation error of void fraction determined by the test method, the void fraction of asphalt pavement core sample cannot be accurately determined by the test method, and the maximum error is 73.5%.
4. After the water damages the core sample by dynamic water flushing instrument, the power relationship equation between CT scan void fraction and leakage strength was established for the traffic lane and shoulder, respectively. It was found that the core sample leakage strength increases with the decrease of core sample CT scan void fraction. Still, when the lane core CT scan void fraction is greater than 5% and shoulder core CT scan void fraction is greater than 7%, the core sample leakage strength increases with the decrease of core sample CT scan void fraction, but the core sample leakage strength increases with the decrease of core sample CT scan void fraction. The change in leakage strength is small. The overall leakage strength of the carriageway core sample is greater than the leakage strength of the shoulder core sample.
5. After water damage destruction of core samples using a dynamic water flushing instrument, an exponential relationship between CT scan void fraction and CPN rutting depth was established for the right of way and shoulder, respectively, and it was found that the core CPN rutting depth increased with increasing CT scan void fraction, and the increasing trend was getting larger. Due to the concentration of coarse aggregate in the shoulder and the strong skeleton effect, the shoulder CPN rutting depth is smaller than the core CPN rutting depth in the right of way.

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