Study on Freeze-Thaw Damage Features of Coal Gangue-Fly Ash-Lime Mixture Based on Computed Tomography Scan

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Keywords: Coal gangue-fly ash-lime (CG-FA-L) mixture, Freeze-thaw, Damage features, Computed tomography (CT) scan.

Abstract. Considering the freeze-thaw damages of coal gangue-fly ash-lime (CG-FA-L) mixture road base, this paper applies the computed tomography (CT) scan to investigate the freeze-thaw damage features of the mixture. Several freeze-thaw tests were carried out to disclose the attenuation law of the frost-resistance coefficient of the mixture. The micro-defect propagation of the CG-FA-L was analyzed by comparing the gray level histograms of the CT images on each specimen before and after freeze-thaw cycles. The loss of cross-sectional area in each specimen was calculated quantitatively by image segmentation. The results show that the frost-resistance index attenuated linearly with the increase in the number of cycles; the defects induced by freeze-thaw cycles were mostly less than 15mm deep, and grew at an increasingly fast speed as the number of cycles surpassed 5; the micro-defect caused by freeze-thaw action mainly affected the depth between 15 and 35mm; under the freeze-thaw cycles, the micro-defects inside the mixture mostly appeared in the cementitious materials of the fly ash and lime; the CT technology was applied satisfactorily in the analysis on the freeze-thaw features of the CG-FA-L mixture.

Introduction

In recent years, the coal gangue-fly ash-lime (CG-FA-L) mixture has been widely adopted as a road base material. The mixture enjoys many advantages, such as strong integrity, high bearing capacity and low engineering cost. In addition, the application of the material produces very few wastes, causing little pollution to the environment [1,2,3]. However, the CG-FA-L mixture may witness a reduction in strength when applied as road base in seasonal frozen region in northern China, due to the freeze-thaw cycles. Thus, it is meaningful to explore the frost-resistance of the mixture. The relevant studies mainly aim at the attenuation degree of unconfined compressive strength, failing to simulate the evolution process of freeze-thaw failure [4,5].

One of the best ways to identify the damage features of material lies in the nondestructive technology of the computed tomography (CT). Using this technology, the structure, composition, material and defect of the object are displayed in the form of a 2D image. More and more scholars have adopted the CT technology to disclose the damage features of various materials. For instance, this technology has been employed to study the particle interaction in mine fillers [6], the damage propagation of rocks under freeze-thaw cycles [7], as well as the damages of spray membrane waterproof material in complex groundwater environment [8]. However, there is no report that uses the CT technology to explore the properties of the CG-FA-L mixture.

In view of the above, this paper introduces CT scan to examine the freeze-thaw damage features of the CG-FA-L mixture. First, the information of the CT image was fully extracted by digital image processing. On this basis, the author investigated the evolution of the CG-FA-L mixture in freeze-thaw failure, and analyzed the relationship between damage variables and freeze-thaw cycles. The research findings shed new light on the frost-resistance of the CG-FA-L mixture.
Methodology

Materials

(1) Coal gangue: The coal gangue samples were collected from a coalmine in Xingtai, northern China’s Hebei Province. With a water adsorption rate of merely 3.58%, the coal gangue enjoys a dense structure and good permeability. Moreover, the samples boast a low burning loss and good stability. The coal gangue samples are of natural grading, with the maximum particle size below 37.5mm.

(2) Lime: This research uses slaked lime purchased from the market in Xingtai. The CaO and MgO content in the lime directly bear on the strength of the CG-FA-L mixture. With the effective CaO and MgO content of 58.58%, the slaked lime belongs to the Level III in the Technical Guidelines for Construction of Highway Roadbases (JTG/T F20-2015) [9].

(3) Fly ash: The fly ash in our test was purchased from the market in Xingtai. The SiO$_2$, Al$_2$O$_3$ and Fe$_2$O$_3$ contents are respectively 60.15%, 30.83% and 4.42%. The burning loss stands at 15.33%. These indices satisfy the provisions in the JTG/T F20-2015.

Test Plan

Freeze-thaw Test Design. First, a high-strength and high-benefit mix ratio was selected as coal gangue: lime: fly ash=73.75: 5.9: 20.35 (dry weight ratio), using the regression model on the relationship between different admixtures and the strength of the CG-FA-L mixture [2]. Next, the optimal water content and maximum dry density of the CG-FA-L mixture were determined as 10.42% and 1.912g/cm$^3$, respectively, through the Proctor compaction test.

After measuring water content, the selected coal gangue, lime and fly ash were mixed at the above ratio, and diluted with tap water to the optimal water content. According to the Test Methods of Materials Stabilized with Inorganic Binders for Highway Engineering (JTG E51-2009) [10], several cylindrical specimens (compaction degree: 96%; diameter: 150mm; height: 150mm) were prepared by static pressure molding and cured by the standard method (temperature: 20±2℃; humidity>95%; duration: 28d).

The JTG E51-2009 specifies that the semi-rigid base material should be cured for 28d or 180d before frost-resistance evaluation. When applied as the road bed, the CG-FA-L mixture will witness a growing strength in the early phase, making the frost-resistance even more important. Therefore, the standard curing period was determined as 28d. In total, 4 specimen groups, each of which contains 9 specimens, were prepared for our test, including one control group and three freeze-thaw groups. The specimens in the three freeze-thaw groups respectively underwent 5, 10 and 15 freeze-thaw cycles.

According to the freeze-thaw test method in the JTG E51-2009, each freeze-thaw cycle consists of a 16h-freezing in a -18℃-cryogenic box, and an 8h-melting in a 20℃-water tank. In the freezing phase, the specimens were placed with an interval of 20mm to facilitate the circulation of cold air. In the melting phase, the water surface was kept 20mm above the top surface of each specimen. The test was terminated when the quality loss reached 5%.

CT Test Design. After being cured for 28d, the control group specimens received strength measurement according to the unconfined compressive strength test in the TG E51-2009. The specimens were relocated to the CT scanner, with their positions marked, and subjected to the initial CT scan. The scanning thickness was 5mm, and 29 images were produced for each specimen. After scanning, the specimens in the three freeze-thaw groups respectively underwent 5, 10 and 15 freeze-thaw cycles. Next, the specimens were relocated to the CT scanner and placed at the marks of the control group specimens in the initial scan, such that the CT images of the freeze-thaw specimens have one-to-one correspondence with those of the control specimens. After scanning, the freeze-thaw specimens received unconfined compressive strength test.
Processing Method

The gray level histogram of each CT image was obtained in three steps. First, the interior image of each specimen was divided into areas of the same size with ImageJ; then, the gray level histogram of the CT image of the specimen was analyzed by commands like Analyze-Histogram; finally, the results were exported via List-File-Save.

The loss of cross-sectional area of each specimen was calculated as follows: To quantify the loss induced by freeze-thaw action, the post-loss specimen area was extracted from the background of the CT image by threshold segmentation. First, the CT image was imported to ImageJ. Next, a proper threshold was defined after analyzing the CT image. After that, the image was segmented into binary images using ImageJ commands like Image-Adjust-Threshold. Then, the size of each binary image was quantified through commands like Analyze-Analyze Particles. Finally, the initial cross-sectional area of the specimen was divided by the loss of cross-sectional area after freeze-thaw, yielding to the loss of cross-sectional area. In the following analysis, the parameters of a specimen measured before and after freeze-thaw cycles are referred to as the initial and final values, respectively.

The results on unconfined compressive strength are recorded in Table 1, where the frost-resistance is measured by the ratio of the final strength to the initial strength (BDR).

Table 1. Unconfined compression strengths and BDR values.

<table>
<thead>
<tr>
<th>Number of freeze-thaw cycles</th>
<th>Unconfined compressive strength (MPa)</th>
<th>BDR (%)</th>
<th>Cv (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>5.84</td>
<td>100</td>
<td>9.42</td>
</tr>
<tr>
<td>5</td>
<td>5.42</td>
<td>92.81</td>
<td>5.54</td>
</tr>
<tr>
<td>10</td>
<td>5.11</td>
<td>87.50</td>
<td>9.00</td>
</tr>
<tr>
<td>15</td>
<td>4.76</td>
<td>81.51</td>
<td>7.78</td>
</tr>
</tbody>
</table>

According to the regression results, the correlation coefficient between the BDR of 28d specimen \( f(x) \), % and the number of freeze-thaw cycles \( x \) was 0.9963, and the relationship between the two parameters can be described as:

\[
 f(x) = -1.2156x + 99.572
\]

As per the Specifications for Design of Highway Asphalt Pavement (JTG D50-2017)\[11\], the 28d specimen of the fly ash-lime road base of expressways or Class 1 highways in heavy frozen region should be greater than 70% after 5 freeze-thaw cycles. As shown in Table 2, the BDR of the CG-FA-L mixture was 92.81% after 5 cycles, 87.50% after 10 cycles, and 81.51% after 15 cycles. The BDR always stayed above 70%, revealing the good frost-resistance of the mixture. Besides, the regression equation shows that the BDR of the mixture attenuated linearly, as the number of freeze-thaw cycles increased to 15.

Analysis on Freeze-Thaw Damage Features

Gray Level Histograms

The specimens D5-1, D10-1 and D15-1 were respectively frozen and melted 5, 10 and 15 times. Figure 1 presents the initial and final 2D images on the 75mm-deep cross-section of these specimens. In the scan images, the high-density areas are brighter than the low-density areas and the pores and cracks, which have the lowest density, are shown in black color. As shown in Figure 1, edge defects were observable on the specimens, which intensified with the increase in the number of freeze-thaw cycles. However, there were no obvious pores or cracks inside the structure. The absence is attributed to the limited accuracy of the CT scanner, which is unable to capture the micro-cracks.

In the absence of large pores or cracks, it is impossible to observe the micro-defect variation from the CT images. In fact, the variation can be inferred from the gray level changes on the CT images.
As a result, the gray level histograms (Figure 2) of the CT images (Figure 1) were plotted to study the micro-defect of the CG-FA-L mixture induced by freeze-thaw action.

Figure 1. The initial and final CT images of several specimens.

Figure 2. (a) Initial and final gray level histograms of D5-1 (depth: 75mm)
action caused micro-defect to the CG-FA-L mixture. After 15 cycles, the gray level histogram of the final CT image still had only one peak, revealing that the rather slow propagation of micro-defect.

(b) Initial and final gray level histograms of D10-1 (depth: 75mm)

(c) Initial and final gray level histograms of D15-1 (depth: 75mm)

Figure 2. Gray level histograms of the CT images.

Freeze-thaw Loss Variable

For better quantification, any pixel was considered as a micro-defect if its gray level fell between 140 and 165, and the loss variable was defined as the number of such pixels to the total number of pixels. As mentioned above, edge defects were observable on the specimens. Through intensive analysis on the CT images, it is found that the surface defects of the specimens were less than 15mm deep. The loss variable was analyzed within the 60mm-radius circle around the center of the cross-section of each specimen, such that the same area was examined in the initial and final images. For each specimen, 23 CT images were subjected to analysis, except those with upper and lower surface defects.

Horizontal Distribution of the Loss Variable. Based on the distance to the center of the circle, the 60mm-radius circle around the center of the cross-section of each specimen was divided into 6 zones. Then, the gray level histogram was plotted for each of the six zones. By comparison, we know that the micro-defects of the CG-FA-L mixture increased with the distance to the center of the circle. The loss variables mostly concentrated in the circular area 40~60mm from the center of the circle. In this area, the loss variables grew at an increasingly fast speed with the increase in the number of freeze-thaw cycles.

Vertical Distribution of the Loss Variable. Starting from the center cross-section of each specimen, the loss variables of the cross-sections 10mm, 20mm, 30mm, 40mm, 50mm and 60mm above or below the center cross-section were measured. The distances of the upper cross-sections to the center cross-section were considered as positive, and those of the lower ones to the center one as negative. On each cross-section, the loss variable was analyzed within the 60mm-radius circle around the center of the cross-section.
By comparison, we know that the micro-defects on the upper and lower cross-sections of the CG-FA-L mixture increased with the distance to the center cross-section. When the distance increased from 40mm to 60mm, the loss variable grew at an increasingly fast speed and mainly concentrated on the upper and lower cross-sections 40mm–60mm away from the center cross-section. With the growth in the number of freeze-thaw cycles, the loss variable of each cross-section was on the rise, and the most obvious increase was observed in the upper and lower cross-sections 40mm–60mm away from the center cross-section.

**The Total Loss Variable and the Loss Variable of Coal Gangue.** In this sub-section, all the area within the 60mm-radius circle around the center of the cross-section, together with the coal gangue inside this area, are taken as the targets. The gray level histogram of the area was plotted and the loss variables of the area and the coal gangue were computed. The results are recorded in Table 2 below.

<table>
<thead>
<tr>
<th>Number of freeze-thaw cycles</th>
<th>Total loss variable (%)</th>
<th>The loss variable of coal gangue (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.73</td>
<td>0.042</td>
</tr>
<tr>
<td>10</td>
<td>1.55</td>
<td>0.071</td>
</tr>
<tr>
<td>15</td>
<td>2.68</td>
<td>0.094</td>
</tr>
</tbody>
</table>

The data in Table 2 show that the loss variable of coal gangue was 0.042% after five cycles within the 60mm-radius circle around the center of the cross-section, while the total loss variable of the area was 0.73% in the same period. Besides, the loss variables of coal gangue were respectively 0.071% and 0.094% after ten and fifteen cycles, while the total loss variables of the area were respectively 1.55% and 2.68%. Obviously, the coal gangue only suffered from a very slight loss, indicating that the freeze-thaw loss of the CG-FA-L mixture mainly comes from the cementitious materials of the fly ash and lime.

**Loss of Cross-Sectional Area**

The author analyzed the initial and final CT images on 23 positions of each specimen in one of the three freeze-thaw specimen groups, and computed the loss of cross-sectional area of each group at different number of freeze-thaw cycles. The loss of cross-sectional area was 0.21% after 5 cycles, 0.89% after 10 cycles and 1.78% after 15 cycles; the loss of cross-sectional area increased faster and faster after the number of cycles surpassed 5.

**Freeze-thaw Damage Features of the CG-FA-L Mixture**

Under fewer than 15 freeze-thaw cycles, the frost-resistance of the CG-FA-L mixture attenuated linearly with the increase in the number of cycles. The defects induced by freeze-thaw cycles were mostly 0–15mm deep, and grew at an increasingly fast speed as the number of cycles surpassed 5. The micro-defect caused by freeze-thaw action mainly affected the depth between 15 and 35mm. In this depth range, the loss variable increased markedly with the growth in the number of cycles. In the depth range of 35–75mm, the loss variables induced by freeze-thaw cycles were small and similar in size, and grew slowly with the increase in the number of cycles. Under the freeze-thaw cycles, the micro-defects inside the mixture mostly appeared in the cementitious materials of the fly ash and lime.

**Conclusions**

(1) The frost-resistance index of the CG-FA-L mixture, which had been cured for 28d under standard conditions, remained above 70% whether after five, ten or fifteen freeze-thaw cycles. The frost-resistance is desirable and in line with the requirements in relevant code. In addition, the frost-resistance index attenuated linearly with the increase in the number of cycles.
(2) Under fewer than 15 freeze-thaw cycles, the defects induced by freeze-thaw cycles were mostly less than 15mm deep, and grew at an increasingly fast speed as the number of cycles surpassed 5. The micro-defect caused by freeze-thaw action mainly affected the depth between 15 and 35mm. In this depth range, the loss variable increased markedly with the growth in the number of cycles.

(3) Under the freeze-thaw cycles, the micro-defects inside the mixture mostly appeared in the cementitious materials of the fly ash and lime.

(4) The CT technology was applied satisfactorily in the analysis on the freeze-thaw features of the CG-FA-L mixture. With the aid of this technology, the author managed to disclose the damage law inside the specimens in an accurate manner, without damaging the CG-FA-L mixture specimens.

Acknowledgements
This research was funded by the Natural Science Foundation of Hebei Province (E2016402079).

References