이미징 기법을 이용한 아스팔트 혼합물의 역학 실험

Digital Image Correlation and its application for material characterization of HMA

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1. Introduction

In recent years, federal and state highway agencies have invested considerable effort in moving towards the mechanistic design of asphalt pavement and asphalt-aggregate mixture. This move has underscored the importance of material testing more than ever. Currently, the Linear Variable Differential Transformer (LVDT) is the most popular means of measuring displacements of asphalt concrete in laboratory testing. LVDTs are fairly inexpensive and simple to operate. However, the LVDT's limitations, due to the contact nature of its mounting method and inability to capture full-field deformations in the specimen, make it clear that advancements in the displacement measurement system will undoubtedly improve the speed and accuracy of asphalt concrete testing that is required in state highway agency laboratories. Since the early 1980s, numerous testing schemes and algorithms for image analysis have been proposed and applied to experimental mechanics due to the rapid advancement in optical instruments and computer technology. One of the leading optical techniques is the Digital Image Correlation (DIC) method.

In this research, the accuracy of DIC measurements is verified using experimental data, and the applicability of DIC to asphalt mixture testing is explored. Strengths and weaknesses of this method are also presented.

2. Digital Image Correlation (DIC)

DIC is a non-contact, full-field displacement/strain analysis method that compares images of deformed specimens with that of an initial, undeformed specimen. The basic setup of the DIC technique requires a digital camera, a lighting system, a frame grabber, a PC, and software for post-analysis. The camera is positioned perpendicular to a specimen having a black and white pattern. The dark-light contrast may be natural, acid-etched, or from an applied speckle pattern. A stable mount is used to maintain a constant distance from the camera to the specimen. The camera is focused and calibrated via software. Video frames are captured, tagged, and stored as the load is applied.

In essence, DIC analysis involves measurement of the grayscale level at each pixel location thus creating a map within the area of interest. Each spot on this map is compared with the initial, undeformed image, and the movement of each pixel in the horizontal and vertical directions is determined, from which displacements and strains are calculated using advanced mathematical techniques. There are some advantages and disadvantages of using DIC for the displacement measurement technique in asphalt mixture testing instead of conventional LVDTs. The advantages are: (1) it is a non-contact system; (2) the amount of time and effort required for specimen preparation is relatively small; (3) it measures full-field displacements from the area of interest; (4) it has post-processing abilities; and (5) it can measure large deformations without losing resolution. There are also weaknesses of DIC if applied to asphalt mixture testing. They are: (1) the image acquisition rate is much slower than with LVDTs; and (2) the area of interest must be visible from the camera. Currently, the fastest image acquisition rate is 100 frames per second in a monotonic test and 10 frames per second in a cyclic test with the synchronization program. Therefore, in a 10 Hz cyclic test for example, images from only peaks may be obtained. However,

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in many asphalt mixture cyclic tests, the information from peaks is sufficient for performance prediction analysis. Another weakness of DIC is that the area of interest must be accessible from the camera since DIC uses the camera as the sensor. Therefore, the temperature chamber used in controlling the test temperature in asphalt mixture testing should have a glass window on the sides where the images are to be captured.

3. Laboratory Experiments

3.1 Specimen Preparation

A 12.5 mm Maryland State Highway Administration (MSHA) Superpave mix design has been adopted for specimen fabrication. Specimens with air void content falling between 3.5 and 4.5% were accepted for testing. Test specimens were cut from the 150 mm diameter; 175 mm high gyratory plugs compacted by the Australian Superpave Gyratory Compactor, Servopac. Two types of specimen were obtained from the gyratory plug: 40 mm wide, 60 mm deep, and 150 mm high prismatic specimens for fracture mechanics testing, and 75 mm diameter, 150 mm high cylindrical specimens for monotonic tension testing. Symmetric double notched (3.5 × 7 mm; 5 × 10 mm) were made in the middle of prismatic specimens using a masonry saw machine. After making notches the specimen surface was cleaned thoroughly using sand paper and an airbrush. This ensured that the surface was smooth without any chemical residues so that a speckle pattern could be uniformly applied. Then, the prepared specimens were painted white with an ordinary spray paint for several light coats. After an even white surface was obtained, the specimen was propped up against a newspaper and black spray nozzle with proper pressure from a certain distance, the uniform-sized speckle pattern was applied onto the surface randomly. The black paint was lightly sprayed several times until the desired uniform speckle pattern density was achieved. The optimum speckle pattern density is an even mix of dark and white areas, producing a pattern that is neither biased towards the white nor the black end of the grayscale. The speckle pattern must be dense enough so that at the desired magnification there are no empty white areas which are detrimental to image analysis accuracy. Four LVDTs (two 75 mm LVDTs; two 50 mm LVDTs) were attached to the sides of the specimens, away from the notches. Two 30 mm LVDTs, spaced evenly, were installed in the middle of the bottom half of the specimen. This location is expected to be outside the failure zone and, therefore, yields information on the unloading behavior of the far field. Fifty mm LVDTs were glued near the front surface where the speckle pattern was applied so that a direct comparison may be made between DIC results and LVDT measurements. Relatively, 75 mm LVDTs were placed near the backside of the specimen where 30 mm LVDTs were placed.

3.2 Test Setup

The distance between the CCD digital camera and the surface of the specimen placed in the temperature chamber was determined for maximum image resolution. Ideally, the camera should be placed far enough away to reduce any error caused by the inclination of the specimen surface. Considering the focus constraints of the telephoto lens (35 mm, NIKON) and space limitations in the laboratory, a distance of approximately 1.2 m away from the specimen surface was chosen and maintained as a camera position throughout testing.

The first picture, a reference image, must be taken when the specimen setup in the testing machine is ready for testing. From the moment of the first shot, the test setup should be secure from any movement until the end of testing. Using the synchronization scheme, the digital camera was triggered automatically whenever the signal reached the tensile peaks throughout the testing. The DIC system used in this research consists of a 1,008 (horizontal) × 1,018 (vertical) resolution CCD digital camera (PULNIX TM-1001) equipped with a frame grabber program, two interfacing boards for image and triggering signal acquisition, and a fiber optic guided illuminator as a light source.

3.3 Testing Program

Monotonic fracture mechanics testing was performed on 40 mm wide prismatic specimen glued to end loading plates at different temperatures. The effect of notch size on process zone evolution was investigated with three different types of notches on 40 mm wide specimens: small notches (3.5 mm wide, 7 mm long); large notches (5 mm wide, 10 mm long); and fatigue-induced cracks. Using DIC, it was expected that one could explain the characteristics of the process zone in terms of size and shape before major cracks dominated the specimen surface. To investigate the applicability of DIC to a curved surface, a 75 × 150 mm cylindrical specimen was loaded with monotonic tension and compared with LVDT measurements. Also, the applicability of DIC to cyclic testing was studied by capturing images at the moment the applied load that is in tension peaks with the aid of a synchronized image acquisition technique.

4. Discussion of Results

4.1 DIC Images

DIC analyzed images of vertical strain captured at various stress states during the monotonic, constant crosshead rate test are presented in Figures 1 and 2 for a prismatic specimen and a cylindrical specimen, respectively. The numbers shown at the top of each legend for ε_{yy} correspond to the numbers marked on the stress-strain curve. Several interesting observations may be made from these figures. First, images for vertical strain, ε_{yy}, clearly show how the strain is localized in the post-peak region. The strain localization due to micro- and macro-cracking is more dispersed in the cylindrical specimen without any intentional notch (Figure 2c) than in the prismatic specimen with double notches (Figure 1c). It was also found that the width of the process zone in notched prismatic specimens is between 4.5 to 5.5 mm irrespective of initial notch sizes. The evolution of the process zone appeared to be dependent on the arrangement of aggregate particles on the specimen surface.

All of the DIC results must be converted from pixels to mechanical units such as millimeters for comparison with LVDT measurements. A magnification factor for this converting process is usually achieved by putting a reference length (i.e., a magnetic ruler) onto the same plane as the specimen surface whenever the first image is taken. According to this study's testing setup, this factor typically ranges from 0.15 to 0.17 mm/pixel. To determine displacement for a specific gauge length using DIC, pixel points were selected that correspond to the locations of the center of the LVDT mounting block.

Vertical displacements measured from 50-mm and 30-mm LVDTs are compared with DIC results in Figure 3 for the notched prismatic specimen subjected to a constant displacement rate of 0.075 mm/sec at 25°C. DIC results agree well with LVDT measurements for a 50-mm gauge length since 50-mm LVDTs were attached close to the specimen surface where the DIC measurements were made, as described previously. It must be noted that the peak load occurred around 10 seconds in this test. Therefore, the larger discrepancy between LVDT and DIC measurements after 15 seconds is due to severe cracking in the specimen. The 30-mm LVDTs were attached to the backside of the specimen where DIC analysis could not be applied. A difference between the two measurements in Figure 3b may be explained by non-uniform deformation along the specimen thickness of 60 mm.

Since the location, shape, and size of the fracture process zone were identified from the DIC analysis, the local strain in the fracture process zone (the FPZ strain) may be more accurately determined. As shown in Figure 4, a rectangular block in the center of observed area was chosen from the DIC image to represent the process zone. Then the process zone strains were calculated along the several selected lines (e.g., lines A, B, C, D, and E).

Figure 5 shows the average strains and the FPZ strains calculated from DIC and the strains calculated from the 50 mm LVDT displacements. The average 50 mm strains were calculated from 50 mm gauge length displacements around the process zone determined by DIC. That is, horizontal lines at the desired gauge points were selected as shown in Figure 4. Using the vertical displacement from each pixel line and the distance between the horizontal lines, which are all in pixels, average vertical strain between the two lines was obtained. Five vertical, equally spaced, imaginary lines in the FPZ were selected for local FPZ strain investigation. As expected, strains near the notches (scan lines A and E) were higher than other strains, which results in crack initiation. It was found that average strains measured and calculated from DIC agree relatively well with 50 mm LVDT strains. Most importantly, the FPZ strains are much higher than the average strains calculated from the 50 mm gauge length, as expected. After the peak load (the vertical dotted line in Figure 5), the difference between FPZ strains and average strains increased dramatically due to strain localization. To demonstrate the importance of this observation, stress-strain curves were generated, shown in Figure 6, using both the average strain and the FPZ strain. It can be seen from this figure that, with the benefits of DIC, a completely different constitutive law (i.e., stress-strain relationship) would be inferred for the FPZ.

4.2 Testing on Cylindrical Specimens

DIC analysis of a cylindrical specimen is not ideal because of the convexity of the specimen surface. The following three factors were prime concerns during preparation, testing, and DIC analysis of cylindrical specimens:

- The application of a uniform speckle pattern on the surface of cylindrical specimens.
- Light condition (possible shade from the curved surface).
- The maximum possible width for reliable DIC analysis.

Although the amount of time needed to paint the curved surface was slightly greater than for flat surfaces, excellent speckle patterns were achieved by rolling the specimen little by little while spraying. Obtaining a uniform light condition over the curved surface from the outside of the temperature chamber was difficult. To determine the maximum possible width for the DIC analysis, four LVDTs (two for a 75-mm gauge length; two for a 100 mm gauge length) were mounted close to the boundary of a 50-mm wide region.

Displacements calculated from the DIC analysis of three regions (left, center, and right) in the 50-mm zone are plotted against the average of 75-mm LVDT measurements in Figure 7. Some discrepancy was observed between the average displacements from the DIC analysis and the LVDT measurements. However, recognizing that the peak load occurred around 200 seconds in this test and that the LVDT locations are not exactly the same as the locations for the DIC analysis, the agreement is considered to be acceptable for most of the test where data are meaningful.

5. Conclusions

A non-contact, full-field displacement measurement technique, DIC, has been successfully applied to the mechanical testing of asphalt concrete mixtures. All the results of DIC were well compared and verified with conventional LVDT measurements for validation. Limited data in this study indicate that DIC may ne applied not only to flat surfaced specimens but also to cylindrical specimens with 75 mm diameter. Also, it was demonstrated that the synchronization program allows the use of DIC in cyclic testing of asphalt mixtures. The full-field measurement and post-processing nature of the DIC analysis allows the investigation of the fracture process zone at the crack tip. The limited test results shown in this paper using the 12.5 mm Superpave mix suggest that the width of the fracture process zone in asphalt concrete is around 3 to 5 mm and hat it has a thin elliptical shape. It is demonstrated that the DIC analysis provides a more accurate constitutive relationship of the fracture process zone than conventional LVDTs due to its full-field measurement and post-processing nature.

6. Acknowledgments

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7. References

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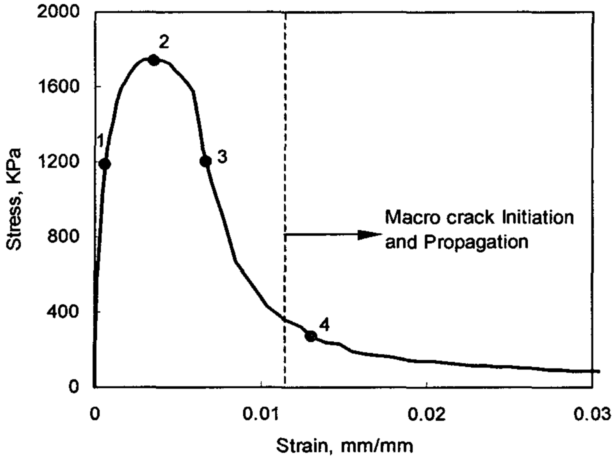


Figure 1a Development of micro cracking and the formation of macro cracks in relation to vertical stress-strain

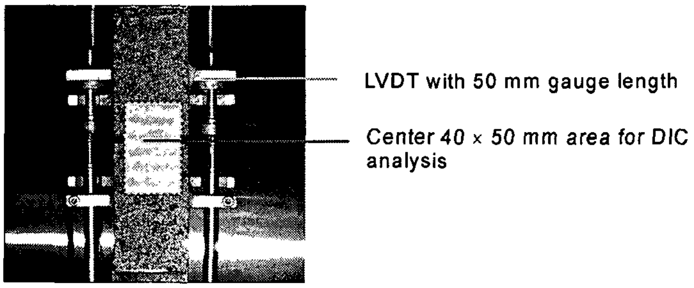


Figure 1b Photo image for DIC analysis of 40 mm wide fracture mechanics specimens

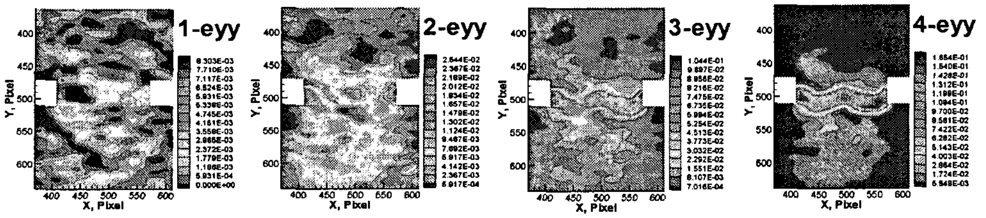


Figure 1c DIC image maps of vertical strain for a prismatic double-notched specimen: center 40 × 50 mm

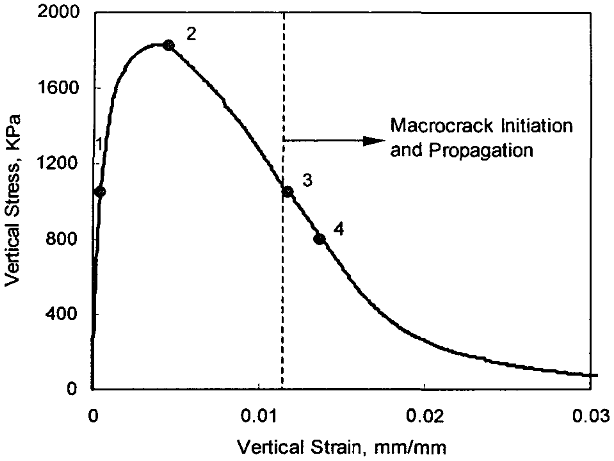


Figure 2a Development of micro cracking and the formation of macro cracks in relation to vertical stress-strain

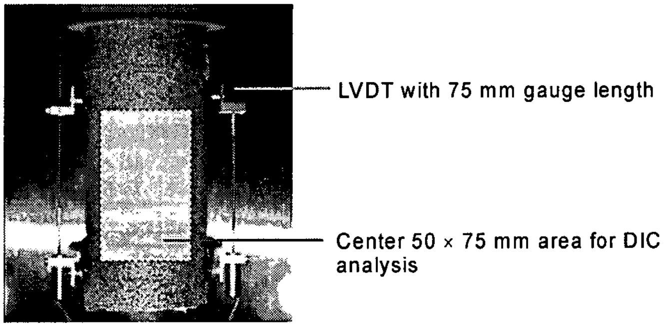


Figure 2b Photo image for DIC analysis of 75 mm diameter cylindrical specimens

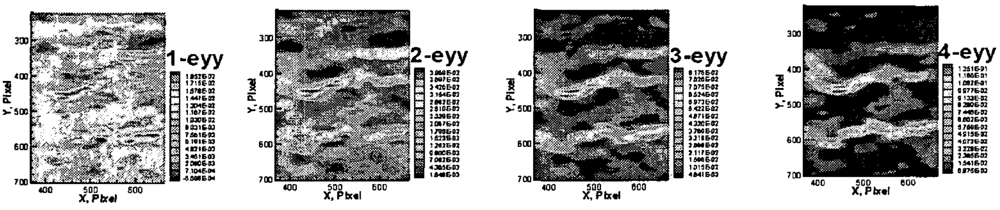
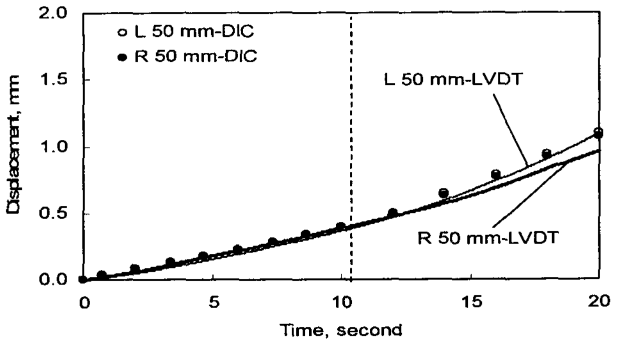
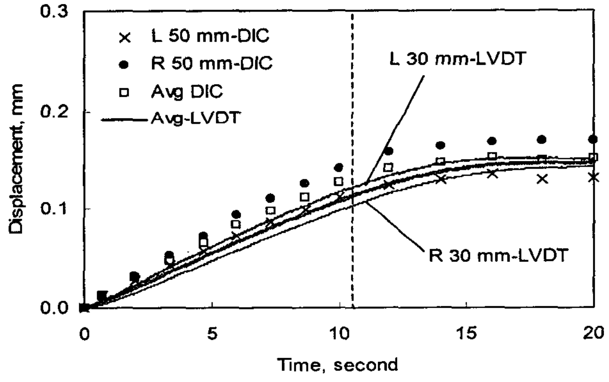


Figure 2c DIC image maps of vertical strain for a cylindrical specimen: center 50 × 75 mm projection plane



(a) For 50 mm gauge length



(b) For 30 mm gauge length

Figure 3 Vertical displacement comparisons

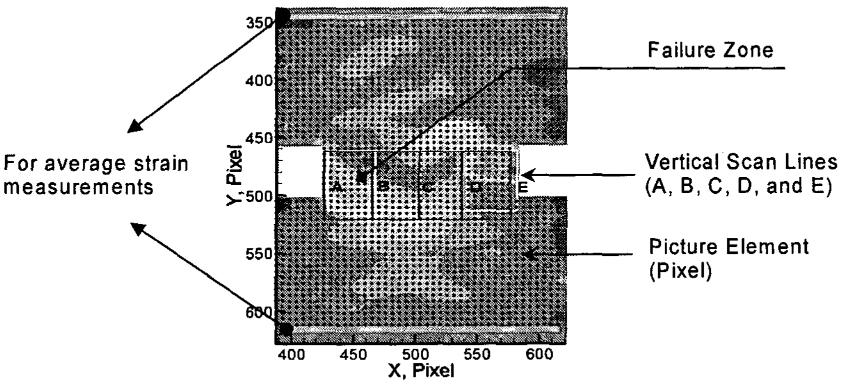


Figure 4 Calculation of average strain and FPZ strain:
DIC-analyzed vertical strain map and corresponding pixel structure

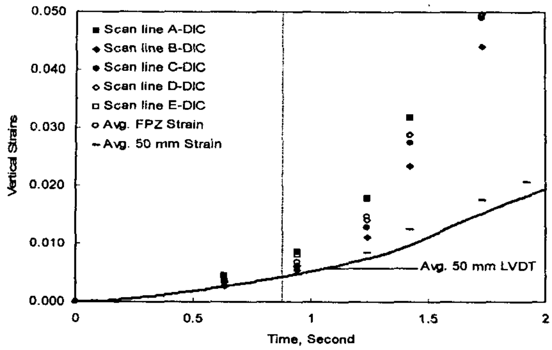


Figure 5 Vertical strain comparison (dashed vertical line denotes the peak load)

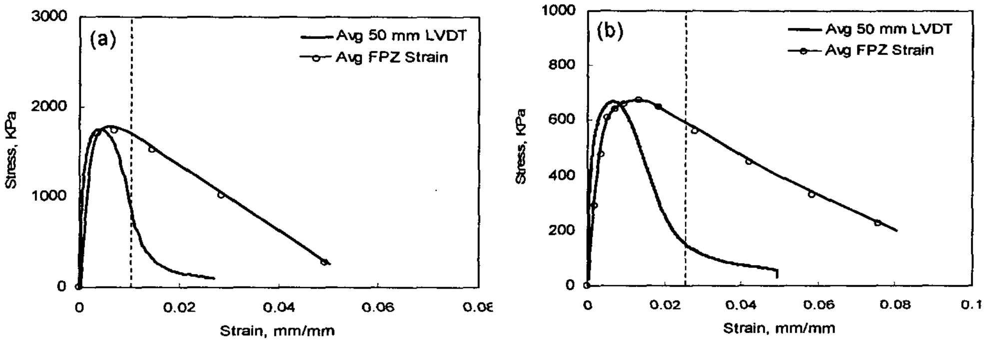


Figure 6 Constitutive relationships using LVDT strain and FPZ strain at 25°C: (a) 0.0045 ε/sec, (b) 0.0005 ε/sec (dashed vertical lines indicate the moment of macro cracks initiation)

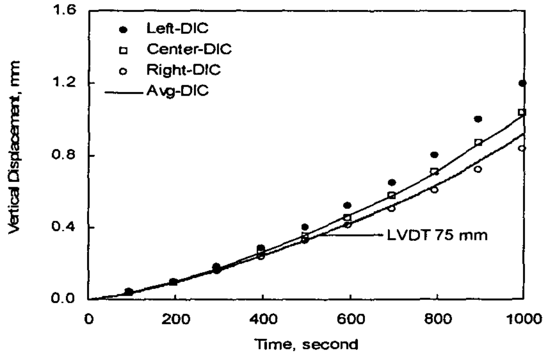


Figure 7 Comparison of vertical displacement measured by LVDTs and DIC with 75 mm gauge length for a cylindrical specimen, subjected to 0.075mm/sec at 25°C