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Characterization of the fracture mode in asphalt at varying temperatures

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CHARACTERIZATION OF THE FRACTURE MODE IN ASPHALT AT VARYING TEMPERATURES

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ABSTRACT: Cracking is a primary mode of distress in asphalt pavements that is generally caused due to repeated traffic loadings, exposure to temperature fluctuations, aging or reflection of cracks in underlying layers. Such cracking can readily lead to higher maintenance and rehabilitation costs for pavement infrastructure, hence negatively affecting the economy both directly and indirectly. To prevent excessive cracking, it is important to understand the cracking characteristics of asphalt mixtures for implementation in road, airport and port pavements. This study aims to investigate the effect of loading and temperature on the cracking behaviour of asphalt using the Indirect Tensile Test (IDT), along with high-speed photography analysis techniques. The results indicate that cracking can occur prior to the asphalt reaching its peak strength in the IDT test. Furthermore, it was observed that increasing temperature can cause a decrease in the peak strength of the asphalt samples and change its fracturing behaviour as well.

INTRODUCTION

The road industry is a vital part of the Australian economy with contributions of over $200 billion in economic value, along with half a million Australians relying on roads for their full-time employment (Roads Australia, 2020). With such high reliance on road networks, the construction and road maintenance are crucial as any premature failures could result in large costs that can negatively affect the social prosperity and economic progress. The main structural elements of a road include pavement and subgrade, which are subjected to repeated mechanical impacts of vehicles and daily changing climatic factors. These mechanical impacts and temperature fluctuations are the most critical factors that govern the overall performance of asphalt mixes as reflected in its strength and fatigue performance (Teltayev and Suppes, 2018).

Depending on the site location, temperatures can vary drastically during a year (e.g. the average temperatures in Australia in a year can change from 3 ^{o}C to 35 ^{o}C between warm days in summer and cool evenings in winter), and these changes can aggravate the damages caused to the asphalt due to temperature fluctuations over time (Aussie Specialist, 2020; Teltayev and Suppes, 2018). However, while many studies have investigated the ultimate fracture strength in asphalt pavements at different temperatures using methods such as Semi-Circular Bend (SCB) and Three-Point Bend tests (Zhou & Newcomb, 2016), there have not been many applications of high-speed photogrammetry in the study of the dominant fracturing/cracking pattern (i.e. the crack initiation and propagation) in asphalt mixes at varying temperatures.

Further, it is understood that for low porosity rock-like geomaterials, the stress required to initiate microcracks (known colloquially as the Crack Initiation point) is considerably less than the material's peak strength (Nicksiar & Martin, 2012). While this has not been thoroughly verified with cracking in asphalt pavements, the authors observed in a recent study that macrocracks could also be identified in asphalt samples well before the sample's peak strength even if the temperature remains unchanged during the test (Serati, et al., 2020). This recent study of the authors was, however, conducted with limited test samples and more investigations were deemed necessary to confirm the initial observations.

With the above objectives in mind, the current work aims to validate whether cracks do indeed appear before an asphalt sample reaches its peak strength during the IDT test. If tensile cracking could occur prior to the maximum load in the IDT method, alternative testing techniques should then be used instead, or an adjustment factor to be applied to compensate for the overestimation of asphalt tensile strength in the IDT method. In addition, this study investigates the effect(s) of varying temperature on both the strength and cracking/fracture pattern of some selected asphalt mixtures.

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METHODOLOGY

Many linear elastic fracture mechanics-based (LEFM) models assume an ideal isotropic and homogenous material when describing crack propagation in a solid. These models also suggest a continuous extension of pre-existing flaws as a method of crack propagation (Serati, et al., 2015; Masoumi, et al., 2017; Roshan, et al., 2018; Serati, et al., 2020). However, asphalt is a heterogeneous and viscoelastic composite material consisting of aggregate, binder, air voids and microstructure with complex geometries. The available LEFM theoretical models are therefore generally inadequate to understand crack propagation behaviour in asphalt mixes. Direct laboratory testing is thus considered as the most accurate and convenient approach for the study of asphalt fracture characterisation, provided the testing equipment is available. Several testing methods have been developed and are widely used, namely the semi-circular bend (SCB), disk-shaped compact tension (DCT), uniaxial thermal stress and strain test (UTSST), Texas overlay test (OT), and the indirect tension (IDT) test (Zhou and Newcomb, 2016; Serati, et al., 2017). The IDT test, in particular, was designed to characterise the static and dynamic cracking performance of asphalt pavements and is classified as a test with excellent ease of sample preparation and good reproducibility (Christensen and Bonaquist, 2004). A simple IDT test configuration is also shown in Figure 1. The IDT test was therefore chosen as the preferred testing method in this study.

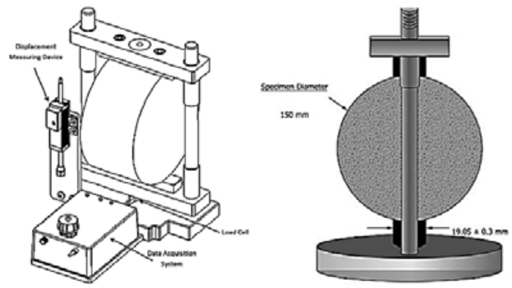


Figure 1: Schematic of the IDT testing configuration (Zhou & Newcomb, 2016)

A total of 15 field-cored asphalt briquettes were used that were prepared using standard laboratory compaction. The samples comprised of 14 mm aggregate with a modified binder (A15E) compacted to 50 blows Marshall compaction. Samples were sprayed with white spray paint (on the face) to provide contrast to the natural dark colour of the asphalt as this contrast aids the recognition of cracking propagation during analysis. In order to test the temperature effect, there were three designated temperature ranges for testing:

- 5 ^{o}C for lower bound temperature analysis;
- Room temperature at 24 ^{o}C; and
- 35 ^{o}C for upper bound temperature analysis.

These temperatures were carefully selected to replicate the temperature ranges observed in Australian climates throughout the year. To develop each target temperature within the samples, five asphalt samples were placed in a refrigerator set to 5 ^{o}C whereas four samples were placed in an oven set at 35 ^{o}C; each sample for more than 72 hours before testing. Samples were then tested immediately (within less than two minutes) after being taken out of the refrigerator/oven to ensure the samples did not transition back into the room temperature and neither cools nor heats up during testing. A Phantom v2012 ultra-high-speed camera was also used to monitor the cracking pattern in tested samples. The camera is capable of capturing images at up to 1,000,000 frames per second (fps) at reduced resolution, and up to 22 kHz at a full resolution of 1280 x 800 pixels (Phantom, 2020). Such capabilities make the camera system a suitable gear for monitoring the cracking process of brittle solids (Serati and Williams, 2015; Serati, et al., 2018; Bahaaddini, et al., 2019). Two sets of displacement sensors were selected to capture horizontal and vertical deformations during loading. The vertical displacement was measured using the load frame signal (after being calibrated to account for the machine deformation) whereas a Linear Variable Differential Transformer (LVDT) sensor (detailed below) was used and connected directly to the samples to record the horizontal expansion.

- Burster 8712-50 Linear Transducer LVDT (Burster, 2020)

- Measurement range is 50 mm
- Linearity is ±0.1%

In order to synchronize the load and displacement signals with the high-speed camera, a high-resolution National Instruments Data Acquisition (NI USB-6221 DAQ) unit was further utilized. An Infrared Light Circuit Unit was designed and connected to the DAQ system to perform preliminary calibration tests to ensure various sources of signals collected during each test (also summarised in Table 1) are in proper synchronization with the high-speed camera recordings. The schematic of the DAQ and the test setups are illustrated in Figure 2 and 3.

Table 1: Data acquisition sources

Data	Source
Load	Instron 4505 load frame
Vertical displacement	Instron 4505 load frame
Horizontal displacement	Linear Variable Differential Transformer (LVDT) sensor
Video capture	Phantom v2012 high-speed camera

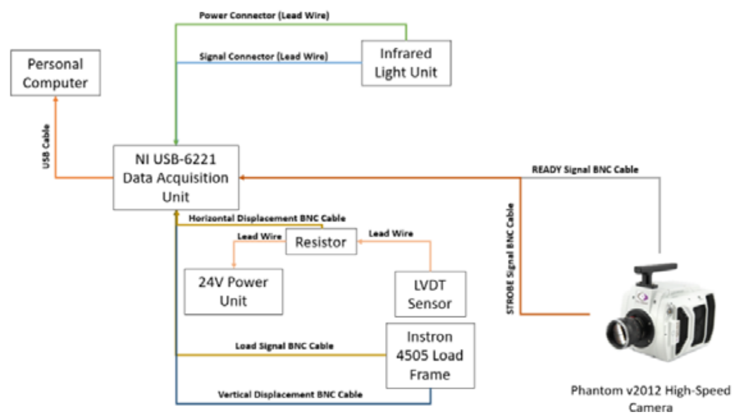


Figure 2: Schematic of data acquisition setup

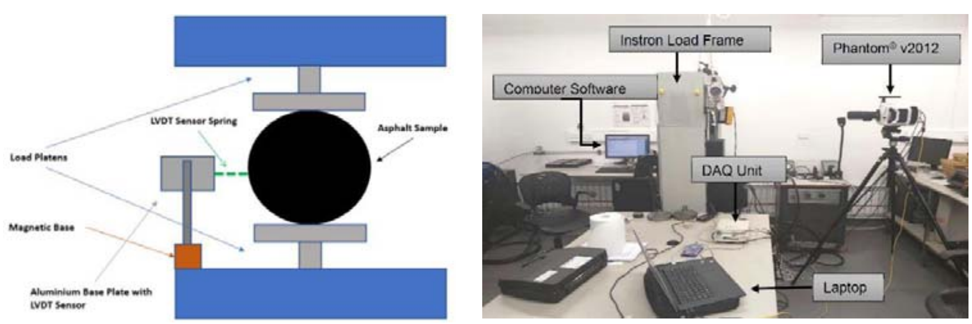


Figure 3: LVDT sensor and camera setup

RESULTS

It should be noted that since displacement measurements using the load frame sensors provides a combined deformation measure of the machine (metal platens) and the asphalt samples, the strain of the metal platens should always be subtracted by means of a preliminary calibration. Therefore, the vertical displacement from the LVDT was compared to that of the readings from the load frame first. Several control tests were run at different displacement rates to provide reference/benchmark points. After the data was acquired from the LVDT and the load frame, the two sets of data were then graphed to find the relationship between the LVDT and the load frame readings. Interestingly, it was found that the load frame readings are in all cases up to 27% higher than the LVDT recordings. A correction factor was then used and applied to the load frame displacement readings to obtain the sample vertical deformation directly. The sample horizontal deformation was also measured using the Burster LVDT transducer, as explained above (see also Figure 3).

Most of the tests were captured at 4,500 fps and a few at higher frequencies of 10,000 fps and above. Camera recordings were then carefully analysed using an image processing software (Phantom Camera Control, PCC; Serati, et al., 2017) to determine the very first frame at which a macro crack was observed on the sample face. For each test, the load at failure, frame number at which the first crack was identified (and its corresponding force and deformations from the load and LVDTs signals), and the sample's tensile strength; were recorded. In some cases, image sharpening techniques using the Laplacian filter was further applied to identify the initial macro crack(s). Table 2 and Figure 4 summarize the results in which areas highlighted by yellow circles represent points on the sample where fresh macro cracks were spotted first at each stress level. All tests were conducted at 120 mm/min.

Table 2: Summary of test results for crack appearances

Sample	Diameter (mm)	Thickness (mm)	Temperature (C)	Tensile strength (MPa)	Maximum load at failure (kN)	Load when the first macrocrack was observed (kN)	Percentage of max load (%)	Cracking pattern
AC14H-01	98.06	61.49	35	0.66	6.25	5.86	93.76	Tensile
AC14H-02	97.74	61.28	35	0.63	5.92	5.01	84.63	Tensile
AC14H-03	98.46	61.34	35	0.67	6.39	1.77	27.70	Tensile
AC14H-04	97.66	61.40	35	0.65	6.11	5.79	94.76	Tensile
			Average	**0.65**	**6.17**			
			Coefficient of Variation (COV)	**2.47%**	**2.80%**			
AC14H-06	98.61	62.93	5	2.57	25.05	17.65	70.46	Shear
AC14H-07	98.58	62.11	5	2.91	28.02	26.40	94.22	Tensile
AC14H-08	98.26	61.74	5	1.33	36.76	36.52	99.35	Shear
AC14H-09	98.34	62.16	5	3.47	33.34	27.39	82.15	Shear
AC14H-10	97.32	62.30	5	2.34	22.30	22.20	99.55	Tensile
			Average	**2.53**	**29.09**			
			Coefficient of Variation (COV)	**28.04%**	**18.21%**			
AC14H-11	98.73	65.35	Room	1.77	17.93	15.92	88.79	Tensile
AC14H-12	98.22	62.34	Room	2.19	21.07	19.26	91.41	Tensile
AC14H-13	98.32	62.12	Room	2.12	20.36	9.84	48.33	Tensile
			Average	**2.03**	**19.79**			
			Coefficient of Variation (COV)	**9.10%**	**6.79%**			

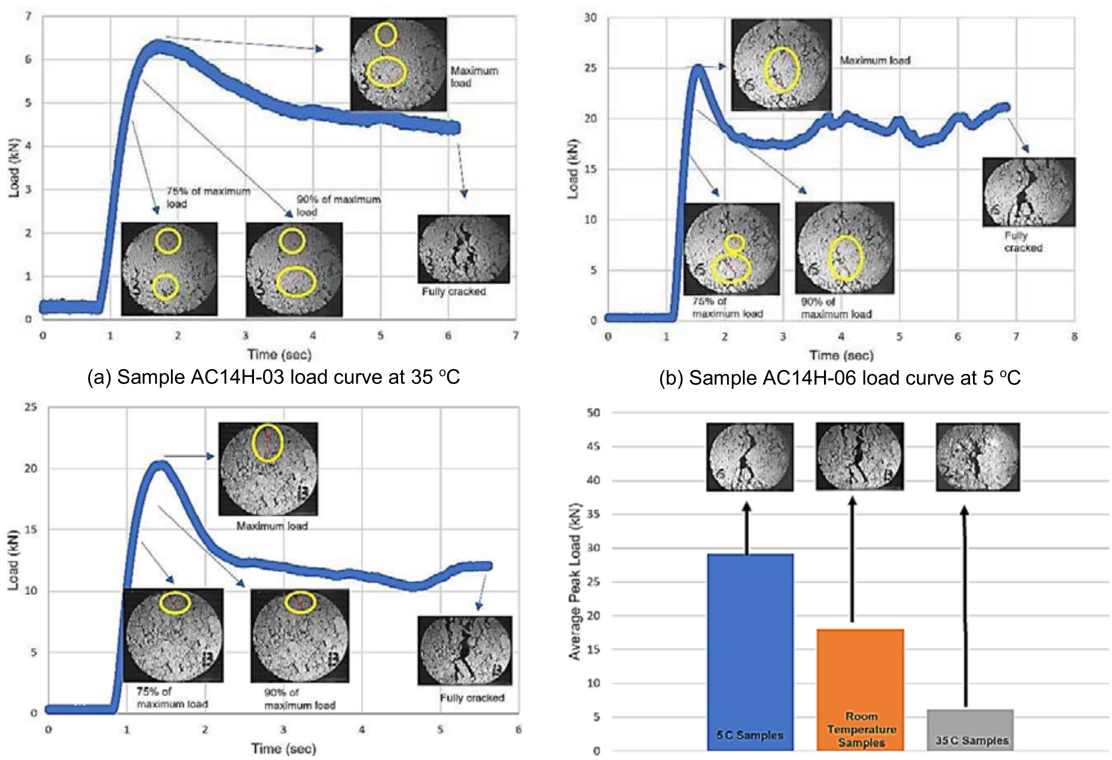
DISCUSSION

When a low-porosity rock is subjected to a uniaxial loading condition, it responds elastically up to the Crack Initiation (CI) point which is defined as the onset of stress-induced damage after the closure of pre-existing cracks. The CI level is approximately one-third of the unconfined compressive strength, but the actual damage becomes only visible after the coalescence of microcracks initiated and extended past the CI stress threshold (Nicksiar and Martin, 2012). Similarly, when testing asphalt under the IDT load configuration, the seven (7) stages below in Table 3 are typically identified, but it is believed that macroscopically visible cracks can only be observed once the peak load is reached (Zhou et al., 2017).

In contrast, several of the obtained results in this study indicated otherwise. That is, the cracks started appearing at various stages prior to the material's maximum strength. Examples of snapshots from high-speed recordings are shown in Figure 4 that demonstrate the state of the sample at the respective points of the load curve. A good potential explanation for this observation could be the transition from tensile to shear cracks happening simultaneously at local points inside a failed IDT asphalt sample. It should be noted that this observation isn't valid during the indirect tensile testing of a rock specimen where the rupture mechanism is solely governed by the initiation and propagation of tensile cracks. An endeavour towards validating this hypothesis using more tests and further numerical modelling is underway. In addition, another objective of this study was to observe the effect of temperature on the behaviour of asphalt under the IDT test. The results show that there is a statistically significant difference between the asphalt strength as the temperature of the sample changes. For example, the cooler the sample, the higher the average peak strength observed. This can be seen more clearly in Table 2 where the cooler samples at 5 °C exhibit almost a 5-times higher peak strength, on average, compared to the samples tested at 35 °C (see also Figure 4).

Table 3: Seven stages of the IDT test's load-displacement curve (Zhou, 2017)

Segment	Stage	Load range and characteristic	Specimen status
Pre-peak load	1	0 – 1/3 peak load	No visible crack
	2	1/3 – 2/3 peak load	
	3	2/3 – peak load	
Peak load	4	Peak load point	Macro-crack starts to appear
Post-peak load	5	Peak load – 2/3 peak load	Macro-crack starting to be visible
	6	2/3 – 1/3 peak load	Crack propagating quickly and more visible
	7	1/3 peak load – 0 load	Specimen separation into 2 or more pieces



(a) Sample AC14H-03 load curve at 35 °C

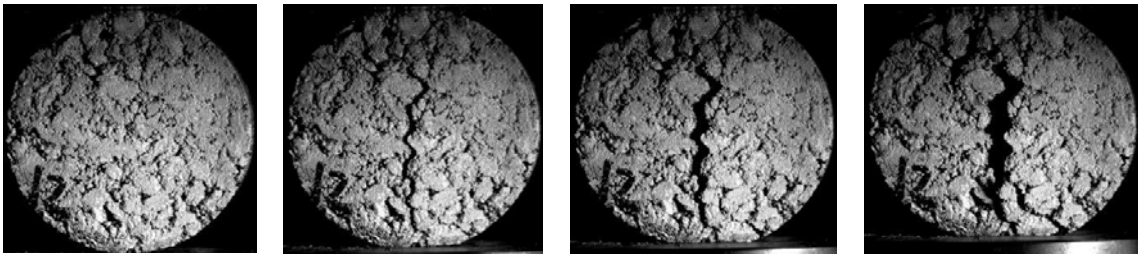
(b) Sample AC14H-06 load curve at 5 °C

(c) Sample AC14H-13 load curve at room temperature

(d) Temperature vs average peak strength

Figure 4: Summary of the test results conducted at varying temperatures

As the temperature increases, the failure in rock often transitions from brittle to a more ductile rupture mechanism, particularly in the post-peak region (Hudson and Harrison, 1997; Syagala, et al., 2014). This behaviour can also clearly be seen in the high-speed recordings obtained with the asphalt samples as shown in Figure 4. The cooler sample at 5 °C exhibits a steeper increase and decrease in the load when compared to the sample tested at higher temperatures. However, when looking at the results in Table 2, there is also a higher variability (i.e. a larger Coefficient of Variation) in the maximum load experienced by the cooler samples. An explanation might be that lower temperatures can result in un-even damage to the asphalt microstructure matrix. More interestingly, some of the cooler samples exhibit a distinct shear cracking/fracturing behaviour in comparison to the single-tensile cracking (which is expected in the IDT test) observed with the samples tested at room and 35 °C temperatures (see Figure 5). Only a limited amount of information was found available in the literature to explain this observation, and further study is underway by the authors' team on what governing parameter(s) could change the cracking pattern/mode in asphalt pavements at low temperatures.



(a) Fracture propagation in AC14H-12 tested at room temperature

(b) Fracture propagation in AC14H-09 tested at 5 °C

Figure 5: Tensile and shear crack developments at 5 °C and 24 °C

CONCLUSION

Crack initiation and propagation in the IDT indirect tensile strength test under varying temperatures was investigated in this study using high-speed photogrammetry. From the results, two key observations can be made: (i) visible macro cracking in asphalt samples prior to the peak strength was confirmed which could be related to the transition of tensile to shear cracks along the grain boundaries, (ii) temperature variation not only influences the strength of asphalt pavement but also the dominant cracking/fracturing mode.

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