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Evaluation of flexural behaviour of cemented pavement material beams using distributed fibre optic sensors

Arooran Sounthararajah [a], Leslie Wong [b], Nhu Nguyen [a], Ha Hong Bui [a], Jayantha Kodikara [a,*]

[a] Department of Civil Engineering, 23 College Walk, Monash University, Clayton Campus, Victoria 3800, Australia
[b] Department of Mechanical and Aerospace Engineering, Monash University, Clayton Campus, Victoria 3800, Australia

HIGHLIGHTS

- Rayleigh-based DFOSs were surface-mounted to CPM beams.
- Static monotonic and cyclic four-point loading tests were performed on the CPM beams.
- The Rayleigh-based DFOS was able to detect crack initiation and growth in the CPM beams.
- The midspan deflection of CPM beams provides a useful method to estimate flexural strain.
- An improved equation was proposed to determine the modulus of CPMs for pavement design.

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ABSTRACT

This paper aims to evaluate the reliability and accuracy of the estimation of flexural strains in cemented pavement material (CPM) beams using a distributed fibre optic sensing technique. Static and dynamic four-point bending tests were performed on CPM beams equipped with distributed fibre optic sensors (DFOSs) and a linear variable differential transducer (LVDT). The strain data recorded by the DFOSs indicated that the midspan deflection measured by LVDT provides a reliable estimation of the flexural strain in CPM beams under both static and dynamic loading conditions. Moreover, the evolution of the strain profiles measured by DFOSs during the flexural tests clearly demonstrated the capability of DFOSs to detect crack initiation and propagation in CPM beams.

1. Introduction

In-situ cement stabilisation is an economical and eco-friendly method to strengthen existing unbound granular pavement bases which are already degraded. Through recycling, this technique helps reduce the utilisation of good quality unbound pavement materials, which are widely manufactured by processing natural rocks. Moreover, cementitiously stabilised pavement materials are being increasingly used globally in the construction of new road pavement bases to cope with increased traffic loads and demand [1,2]. The cement stabilisation process involves the addition of measured quantities of cement (typically, 3–6% by dry mass of the unbound pavement materials) to the pavement materials, mixing with water at the optimum moisture content and compaction of the stabilised mixture to its optimum point [3,4]. The addition of cement in sufficient quantities transmutes the unbound

Abbreviations: B, beam width; CPM, cemented pavement material; CTB, cement-treated base; DFOS, distributed fibre optic sensor; E_{design}, design modulus; E_{flex}, flexural modulus; E_{secant}, secant flexural modulus; GP, general purpose; H, beam height; HRB, Holcim road base; L, span length; LVDT, linear variable differential transducer; ODiSI, optical distributed sensor interrogator; OFDR, optical frequency domain reflectometry; P_{break}, breaking load; P_{cyclic}, applied cyclic load; P_{max}, maximum applied load; P_{min}, minimum applied load; y, distance from the neutral axis of the beam; $\delta_{cyclic,mid}$, cyclic flexural deflection at midspan; δ_{flex}, flexural deflection; $\delta_{flex,mid}$, flexural deflection at midspan; $\delta_{max,mid}$, total midspan vertical deflection; $\delta_{min,mid}$, minimum midspan vertical deflection; $\delta_{plastic,mid}$, permanent midspan vertical deflection; ε, strain; $\varepsilon_{cyclic,mid}$, cyclic midspan flexural strain; ε_{flex}, flexural strain; $\varepsilon_{flex,mid}$, midspan flexural strain; $\varepsilon_{plastic,mid}$, plastic strain at midspan; σ_{cyclic}, cyclic flexural stress; σ_{max}, maximum flexural stress; σ_{min}, minimum flexural stress; σ_0, flexural strength.

* Corresponding author.
E-mail addresses: arooran.sounthararajah@monash.edu (A. Sounthararajah), leslie.wong@monash.edu (L. Wong), nguyen.nhu@monash.edu (N. Nguyen), ha.bui@monash.edu (H.H. Bui), jayantha.kodikara@monash.edu (J. Kodikara).

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pavement materials to bound materials, which can be referred to as cemented pavement materials (CPMs). CPMs exhibiting flexural moduli between 5 GPa and 20 GPa and flexural strengths between 0.65 MPa and 3.5 MPa have been reported [5,6]. However, they are prone to shrinkage cracking caused by moisture variation and thermal effects [7,8].

A pavement base constructed using CPMs, viz., cement-treated base (CTB), continues to gain strength and stiffness with time, even under traffic loads [9,10]. CTB is the superior layer of the pavement structure, which acts like a beam in service to resist heavy traffic loading [11]. The primary distress mechanism observed in CTB layers is tensile fatigue due to repeated application of traffic-induced flexural stresses at the bottom of the CTB (known as bottom-up cracking). For pavement design purposes, the four-point bending test is most often employed to characterise the flexural properties of CPM beams, such as flexural modulus and flexural strain at fracture, in the laboratory [6,12–14]. This test is considered to simulate more closely the bending stress/strain gradients generated in CTB by heavy traffic loading. Many laboratory-based studies have been undertaken on the flexural fatigue performance of CPM beams, and several fatigue models have been developed and used to estimate the in-service fatigue life of CTBs [13–17]. For instance, the strain-based fatigue models given in Eqs. (1) and (2) have been used in Australia and South Africa, respectively [18,19], for the structural design of CTBs. These fatigue models were primarily developed in terms of the flexural modulus and flexural strain of CPM beams subjected to cyclic four-point bending.

$$N = RF\left[\frac{\frac{113{,}000}{E_{flex}^{0.804}} + 191}{\mu\varepsilon}\right]^{m} \quad (1)$$

$$\log N = 9.1\left[1 - \frac{d_s\varepsilon}{\varepsilon_b}\right] \quad (2)$$

where, N = allowable number of load repetitions; E_{flex} = flexural modulus of the CPM (MPa); $\mu\varepsilon$ = load-induced tensile strain at the base of the CPM (microstrain); m = load damage exponent (12.0 for CPMs); RF = reliability factor for CPM fatigue; ε = maximum traffic-induced tensile strain at the bottom the CTB (microstrain); ε_b = tensile strain at fracture measured by static beam flexure (microstrain); and d_s = factor to account for shrinkage cracking in CTB.

In addition to materials testing and pavement design practices, the reliability and accuracy of the measurement of these flexural properties are vital for successful pavement design and construction. For example, the low flexural modulus of CPMs creates high flexural stresses at the bottom of the CTB layer under actual traffic loading, which can eventually lead to premature failure of the pavement. The flexural test assumes the applicability of the classical beam theory to calculate the flexural strain and modulus of the CPM beams using their measured midspan deflection [12,20]. In addition, linear variable differential transducers (LVDTs) are generally employed to measure the midspan vertical deflection of the beam samples in the flexural tests. Table 1 lists the factors which give rise to the erroneous calculation of the flexural strain in CPM beams. During the low-cycle fatigue testing of CPM beams, the use of classical beam theory in conjunction with the assumption of linear elastic material behaviour remains inaccurate [21], engendering erroneous strain-based fatigue models for pavement design. Therefore, there appears to be a need for scrutiny of the flexural strain calculations.

In the past few decades, distributed fibre optic sensors (DFOSs) have drawn a substantial amount of research attention in a broad range of civil engineering applications, by virtue of their inherent advantages of large-scale monitoring, long-term stability, high sensitivity and accuracy, reliability, light weight, corrosion resistance and flexibility [22–25]. With appropriate fibre installation and termination, DFOSs can measure the same strain the host structure experiences. Basically, DFOSs function by sending a light wave into the optical fibre and measuring the backscattered light (backscattering occurs due to imperfections along the fibre) reflected from the entire optical fibre. Two main different types of scattering, namely, linear scattering (e.g. Rayleigh scattering) and non-linear scattering (e.g. Brillouin and Raman scattering), can take place in an optical fibre.

Rayleigh scattering is caused by random fluctuations of the incident light (photons) in the index profile along the fibre length and is sensitive to both strain and temperature. In the Rayleigh scattering process, the energy of the incident light is conserved and there is no frequency shift [24,26]. The particular fibre optic sensing system discussed in this paper employs the Rayleigh scattering technique. Rayleigh-based DFOSs have been shown to be an effective and promising strain measurement technique for several construction materials, such as reinforced concrete. Henault et al. [27] used this sensing technique to monitor the mechanical behaviour of reinforced concrete beams subjected to flexure and demonstrated that the distributed fibre optic measurements were consistent with those of conventional sensors. Davis et al. [28] also used this sensing system to measure the effects of corrosion of reinforcing steel bars on the steel-concrete bond.

Brillouin and Raman scattering are non-linear processes, as they are both associated with some frequency shifts. The former is caused by the scattering of sound waves, while the latter is caused by the interaction of light waves with molecular vibrations in the medium [29]. Researchers have affirmed that Raman scattering is sensitive to changes in temperature only, whereas Brillouin scattering is sensitive to both temperature and strain changes [30]. The use of Brillouin-based DFOSs for the performance monitoring of reinforced concrete [31,32] and steel structural elements [33,34] has been ongoing for the past few decades. However, this sensing technology is still facing the challenge of detecting a truly dynamic response with high spatial resolution.

This paper principally focuses on the assessment of the reliability and accuracy of the estimation of flexural strains in CPM beams using a Rayleigh-based distributed fibre optic sensing system. The next section provides a detailed description of the experimental program, including the sample preparation, the fibre installation

Table 1
Factors which may affect calculated flexural strain in CPM beams subjected to cyclic four-point loading.

Factors affecting computed strain[a]
1. Inhomogeneity and anisotropy of beam material
2. Non-linear elastic behaviour of CPMs after a certain stress level
3. Irregularity of beam cross-section
4. Inaccuracy in the LVDT deflection measurement caused by particle crushing at the supports and vibration of loading rollers during cyclic loading
5. Human errors in dimensional measurements and specimen positioning
6. Pre-existing internal defects and microcracks in beam specimens

[a] Flexural strain calculation using midspan deflection measured by LVDT.