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Using accelerated pavement testing to examine traffic opening criteria for concrete pavements

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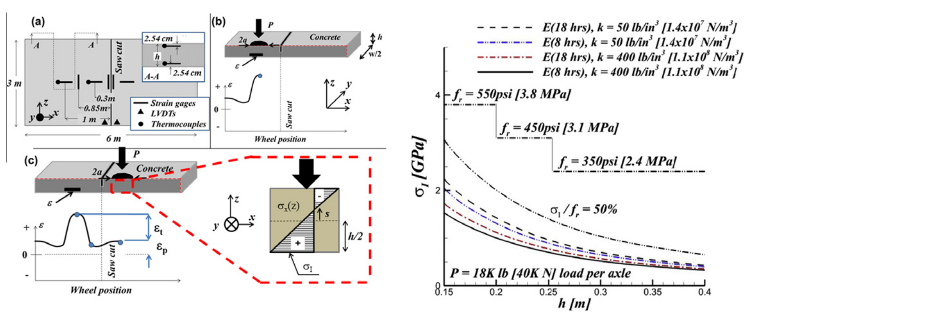
HIGHLIGHTS

- Concrete pavements opened to traffic at early ages were examined experimentally.
- An accelerated pavement testing (APT) facility was employed to provide data.
- Analytical and finite element models were employed to predict critical stresses.
- A new criterion based on time-dependent changes of concrete strength is proposed.

GRAPHICAL ABSTRACT



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ABSTRACT

The risk of cracking in a concrete pavement that is opened to traffic at early ages is related to the maximum tensile stress σ_I, that develops in the pavement and its relationship to the measured, age dependent, flexural strength of a beam, f_r. The stress that develops in the pavement is due to several factors including traffic loading and restrained volume change caused by thermal or hygral variations. The stress that develops is also dependent on the time-dependent mechanical properties, pavement thickness, and subgrade stiffness. There is a strong incentive to open many pavements to traffic as early as possible to allow construction traffic or traffic from the traveling public to use the pavement. However, if the pavement is opened to traffic too early, cracking may occur that may compromise the service life of the pavement. The purpose of this paper is two-fold: (1) to examine the current opening strength requirements for concrete pavements (typically a flexural strength from beams, f_r) and (2) to propose a criterion based on the time-dependent changes of σ_I/f_r which accounts for pavement thickness and subgrade stiffness without adding unnecessary risk for premature cracking. An accelerated pavement testing (APT) facility was used to test concrete pavements that are opened to traffic at an early age to provide data that can be compared with an analytical model to determine the effective σ_I/f_r based on the relevant features of the concrete pavement, the subgrade, and the traffic load. It is anticipated that this type of opening criteria can help the decision makers in two ways: (1) it can open pavement sections earlier thereby reducing construction time and (2) it may help to minimize the use of materials with overly accelerated strength gain that are suspected to be more susceptible to develop damage at early ages than materials that gain strength more slowly.

1. Introduction

At early ages concrete pavements are exposed to loading coming from: (1) wheel loads from construction or user traffic, (2) autogenous and thermal volume changes coming from the

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hydraulic reaction, and (3) shrinkage and thermal volume changes (e.g., curling or warping) caused by environmental variations in humidity and temperature. If the stresses caused by these loads are sufficiently high (as compared to the time-dependent strength of concrete) they can impact the potential for cracking. A general rule of thumb is that if the maximum tensile stress remains below 50% of the tensile strength f_t, the concrete can be consider to behave as linear elastically [1–3] with only limited micro-cracking. However if the maximum tensile stress exceeds 50% of the tensile strength micro-cracking can occur that can lead to nonlinear stress–strain behavior and fatigue susceptibility which may result in this damage developing over time reducing the service life of the concrete pavement [4,5].

Over the last several decades the rate of strength development of concrete paving mixtures has increased [6]. This can occur due to an increase in cement content, reduced water to cement ratios (w/c), and the cement being ground more finely [7–10]. Higher alkali contents and changes in the relative proportions of the calcium silicate which have increased the proportion of tri-calcium silicate (as compared to the proportion of di-calcium silicate) are also frequently suggested to be responsible for the increase of the rate of the strength development. At the same time many DOT's and contractors have worked to develop mixtures that attain higher early strength to reduce the time it takes to open concrete pavements to traffic, thus reducing the need for separate haul and working platforms or the impact of construction delays on the traveling public. As such, it is not uncommon to see concrete mixtures that gain more than 50–80% of their strength within the first several hours to a day after placement [11]. For example, a paving mixture that is typical of those in the state of Indiana may develop 60% of its 90 day strength by an age of 18 h and 90% of its 90 day strength after 7 days [12].

However, the use of concrete with a higher early-age strength can result in higher pavement costs (due to the use of higher cement contents), reduced strength gain at later ages, increased potential for aggregate fracture thus reducing aggregate interlock which helps to transfer stress across the joint [13]. High early-age strength concrete also reduces the potential of using mixtures/pavements with lower carbon footprint, e.g. mixtures with less cement or mixtures when a large volume of cement is replaced with supplementary materials [14,15]. Further, pavements that have higher early strengths might be less prone to crack as designed at saw-cuts and longitudinal joints [16]. This may lead to random cracking [17–19] or joints that do not crack [20] and hold moisture resulting in potential durability issues affecting the life span of the material [21].

Pavement design theory is largely based on flexural stress. As a result, it is common for agencies to use flexural strength, f_r, as an opening-to-traffic criterion. It needs to be remembered that the flexural strength, f_r, is not interchangeable with the tensile strength, f_t, as the geometry of the sample influences the strength due to micro-cracking and pre-critical crack growth at the bottom fiber. For quasi-brittle materials, like concrete, a brittleness number can be used which accounts for characteristic structural dimension and the characteristic material size [22–24]. Hillerborg showed that the ratio f_r/f_t of unreinforced concrete depends on the ratio between the beam depth (H) and the critical crack depth (l_c); ranging from $2 > f_r/f_t > 1$ for $H/l_c \to 0$ and $H/l_c > 5$ respectively [23]. For a typical bending test specimen (typical ASTM standard 6×6 in. [152×152 mm] cross sectional testing geometry) f_r/f_t ranges from 1.0 to 1.2 [25].

In the Midwestern region of the US, the Departments of Transportation define the time for opening to traffic based on the critical value of flexural strength. Specifically, f_r for Michigan (MDOT) and Indiana (INDOT) is 550 psi [3.8 MPa], while f_r for Illinois (IDOT) is 600 psi [4.1 MPa] [26]. However it should be noted that the INDOT requirement of f_r is equivalent to the strength of a simply supported beam with third-point loading, while MDOT and IDOT requirements of f_r are equivalent to the strength of a simply support beam with center point loading. For the same concrete material, the f_r obtained from third-point loading is typically 15% lower than those from a center-point loading due to the potential for a flaw associated to an extended area subject to damage between loading points [27,28]. This would imply that the INDOT has a higher opening strength with an estimated value of 630 psi [4.34 MPa] if center point loading was used. Research is needed to better understand how design criteria, construction operations, and mixture proportions are related to long-term performance. This work examines the current DOT requirements for opening a pavement to traffic or for use as a haul road for construction traffic. Specifically, it is believed that changes over the last several decades in the specifications of pavement thickness, the reactivity of the new materials, and the construction speed could enable these opening criteria to be reevaluated. Reexamining opening requirements could result in an effort to potentially homogenize this opening criterion and to place this decision on more fundamental base.

The APT facility of the INDOT Research Division in West Lafayette (Indiana) was used in this research [29,30]. This experimental apparatus enables concrete pavements to be loaded with simulated traffic conditions in an environmentally controlled facility.

2. Research approach

2.1. Experimental methodology

Four concrete pavements sections were constructed using an accelerated pavement testing facility using a single concrete mixture with the intention of evaluating two variables: (1) loading time (based on flexural tests and maturity), and (2) pavement thickness. Table 1 summarizes the critical information for each of the concrete pavements tested in this study:

The first two pavement lanes (1 and 2) had a thickness (h) of 10 in. [0.254 m], a length of 20 ft [6 m] and a width (w) of 10 ft [3 m]. The other two other pavement lanes (3 and 4) had a thickness of 5 in. [0.127 m], a length of 20 ft [6 m] and a width of 6.6 ft [2 m]. The concrete mixture was a typical commercially produced INDOT ready-mixed concrete paving mixture (i.e., it has been used in several sections of the SR-26 in Lafayette, Indiana [4]) with a water-to-cement ratio (w/c) of 0.42, 22% of the cement was replaced by fly ash replacement of cement by mass, and a fine and coarse aggregate content of 1412 lbs/yd^3 [838 kg/m^3] and 1750 lbs/yd^3 [1038 kg/m^3] respectively. The concrete was designed to have an air content of 6.5%. Dowel bars were installed at the joint of each pavement section at mid height in the middle of each lane to provide a mechanical connection between slabs after the saw-cut was placed. All the pavements were covered after casting with a plastic film until saw-cut (at 8 h) to minimize moisture loss similar to a curing compound.

To determine the time at which each concrete pavement was opened to traffic, the temperature of the concrete pavement was continuously monitored. A Nurse-Saul maturity approach was used to estimate the time dependent flexural strength as described in ASTM C1074 [31] as this is the procedure currently used by INDOT. In addition to the concrete used in the construction of the pavements, concrete beams were cast ($6 \times 6 \times 21$ in. [$152 \times 152 \times 533$ mm]) and their flexural strength were tested following AASHTO T 97-10 (third point load) at the time the opening maturity was reached to determine the strength [25].