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Impact of variability of mechanical and thermal properties of concrete on predicted performance of jointed plain concrete pavements

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Abstract

The performance of jointed plain concrete pavement is affected by various design parameters including mechanical and thermal properties of concrete. Out of these, coefficient of thermal expansion, elastic modulus and modulus of rupture are a few important ones and to evaluate the effects of these material properties on pavement performance, simulations were carried out in MEPDG. All other design parameters such as traffic, design life, climate and road bed soil conditions were considered as constant and pavement performance was evaluated. The simulation results appreciated that with an increase in coefficient of thermal expansion of concrete, the pavement performance was adversely affected. In addition, with an increase in elastic modulus and modulus of rupture values of concrete, the strength of concrete increases and resultantly an improved pavement performance was obtained. It became evident that these material parameters should be carefully considered while designing a rigid pavement.

Keywords: Coefficient of thermal expansion (CTE); Modulus of rupture (MOR); Jointed plain concrete pavement (JPCP); Mechanistic empirical pavement design guide (MEPDG); Transverse cracking; Joint faulting

1. Introduction

A number of factors including material characteristics, climatic factors, anticipated traffic conditions, design life, expected performance parameters and roadbed soil conditions affect design and performance of concrete pavement. Of these, coefficient of thermal expansion (CTE), elastic modulus and modulus of rupture (MOR) are a few important inputs. Various pavement characteristics like cross-section, design life, serviceability and cracking depend partly on these factors. Although the history of rigid pavement is quite old, the first concrete pavement in United States dates back to 1891. However, unfortunately, accurate determination of these material properties could not become a part of the design process until the evolution of Mechanistic Empirical Pavement Design Guide (MEPDG) and AASHTO Ware ME Pavement design software, around the last decade. MEPDG is a combination of both mechanistic and empirical approaches for designing and performance prediction of pavements. While considering all other inputs like traffic, climatic and material, it also takes into account CTE values, elastic modulus and modulus of rupture of concrete for rigid pavement design, and determination of pavement performance. MEPDG evaluates the performance of concrete pavement over the designed life by predicting the performance parameters, which are international roughness index (IRI), mean joint

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faulting and percentage of slabs with transverse cracking. Tanesi et al. worked to determine the effect of the variability of the CTE test on the predicted pavement performance. He performed a sensitivity analysis by varying the CTE values on a single jointed plain concrete pavement design. He found that with the increase in CTE value, the percentage of slabs with transverse cracking also increases [1].

Hein conducted his research and described that thermal expansion and contraction of a concrete pavement can have a significant effect on its performance. Thermal contraction can result in transverse cracking of slabs depending on the joint spacing. Thermal effects also impact slab bending and curling and when joints/edges are curled upwards, they do not have full contact with the base and are subject to cracking under traffic loading. This could be particularly significant for long, thin slabs under heavy, frequent loading [2]. McCarthy et al. found the precision required for measuring the CTE of concrete for use in the MEPDG. They found that a precision of ±0.5 micro-strain/°C appears to have a relatively small impact on the predicted distress and consequently a smaller impact on the required pavement design thickness. However, a difference of 0.5 micro-strain/°C does have a significant impact on the service life in terms of number of years prior to exceeding the distress limit for cracking. Thus, when considering the impact of changes in CTE on predicted service life, the impact is much more sensitive and may be carefully considered [3].

Rao et al. conducted study on curling and warping in JPCP based on temperature and moisture conditions at the time of paving and immediately following construction with field data collected from fully instrumented sections in Arizona and Minnesota, including the temperature data through slab thickness at different times of the day. They concluded that in addition to actual temperature gradients, the effects of built-in curling, shrinkage and creep have to be considered in pavement analysis [4]. Selezneva et al. identified the material characteristics of concrete including strength, CTE and ultimate shrinkage as the key design factors that affect the structural performance of continuously reinforced concrete pavements [5]. Mirsayar et al. investigated the lift-off in concrete slab by evaluating the effects of climatically induced contraction stress and the material properties of the pavement structure by examining the deformation of the slab and the developed stress field around the interface crack tip and found that the relative elastic modulus and the contraction stress significantly influence the stress and displacement fields around the crack tip. The relative slab displacement at the point where the maximum movement occurs is remarkably affected by the relative elastic modulus. For design purposes, for a subbase with a known stiffness, a stiffer concrete should be used to minimize lift-off effects and to diminish the tendency of the interface crack to open. Therefore, one should design the pavement structure on the basis of the material properties of the concrete slab and the subgrade [6]. Vandenbossche et al. evaluated the effects of concrete material properties, pavement structural parameters and the MEPDG standard fatigue damage-cracking performance curve on slab cracking predictions. The sensitivity analysis of impact of CTE, MOR and elastic modulus suggested that small changes in input values for these properties can lead to significant changes in predicted performance [7].

This study focuses on impact of CTE, elastic modulus and MOR on performance of jointed plain concrete pavement (JPCP). JPCP is a commonly used concrete pavement, which uses contraction/transverse joints to control cracking, and there is no reinforcing steel. For the purpose of this study, simulations were conducted in AASHTO Ware ME Pavement design software and the sensitivity analysis was carried out to analyze the impact of these material properties on the terminal pavement performance parameters and the performance over the design life of JPCP.

2. Impact of coefficient of thermal expansion on pavement performance

2.1. Coefficient of thermal expansion

All materials expand and contract to some extent as their temperatures rise or fall. The CTE is a measure of a material's expansion or contraction with temperature. Because the length changes associated with thermal expansion are very small, the CTE is usually expressed in micro-strains per unit temperature change. The test method to determine the CTE was first accepted as an American Association of State Highway and Transportation Officials (AASHTO) provisional test method TP 60 in 2000 and became a full test method T336 in 2009 [8]. The CTE of Portland cement concrete (PCC) ranges from about 7.2 to 14.4 micro-strains/°C (4 to 8 micro-strains/°F) and an average value of 9.9 micro-strains/°C (5.5 micro-strains/°F) is commonly used in pavement design. The range of CTE values for different concretes reflects the variation in the CTE of the concrete's component materials. For example, concrete containing limestone aggregate has a lower CTE than concrete containing siliceous aggregate. Because aggregate comprises about 70% of the concrete, aggregate type has the greatest effect on the CTE of concrete. Jahangirnejad and his team conducted research on CTE of PCC produced with various types of aggregates. They concluded that the magnitude of the measured CTE of PCC varies with aggregate geology. The CTE of hardened cement paste also affects the CTE of concrete [9]. Shin and Chung found that the measured CTEs at various ages (3, 5, 7, 14, 28, 60, 90 days) fluctuates within 0.36 micro-strains/°C (0.2 micro-strain/°F) and the age of concrete, statistically have no significant effect on CTE [10].

2.2. Importance of coefficient of thermal expansion in JPCP

CTE of PCC is a very important parameter in concrete pavement analysis because the magnitudes of temperature related pavement deformations are directly proportional