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

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Received 29 February 2016; received in revised form 3 August 2016; accepted 15 September 2016

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.

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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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Peer review under responsibility of Chinese Society of Pavement Engineering.
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]. Seleznева 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-strains/°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
to this value during early ages (i.e., within 72 h of paving) as well as during the pavement design life. Further, these deformations, in combination with the restraint offered by the base layer and slab weight, affect the resulting curling stresses and axial stresses in the hardened slab both during early stages and in the long term. Using an average value may therefore lead to erroneous assumptions about the pavement’s thermal response and possible distress. Accurate values of the CTE are needed to predict potential thermally induced movements in a concrete pavement. Mallela et al. found that CTE affects the following aspects of pavement performance [11]:

- Early-age or premature random cracking if the excessive longitudinal slab movement (i.e., movement in the direction of traffic) caused by high CTE concrete is resisted by restraint forces (e.g., slab–base friction).
- Higher mid-panel transverse and longitudinal fatigue cracking caused by higher curling stresses.
- Higher amounts of faulting caused by a greater loss of slab support at the time of construction, larger joint openings during adverse seasons, and greater corner deflections from curling.

2.3. Effects of coarse aggregate content on coefficient of thermal expansion

Cement paste has a higher thermal coefficient than that of coarse aggregate. Won [12] did his research on effects of coarse aggregate in which a batch of concrete was made, and cement paste was separated by a wet sieve. Two cylinders were cast with cement paste only. Another two cylinders were made with 25% volume with coarse aggregate and two additional cylinders made with 50% volume with coarse aggregate. CTE testing was done on these cylinders. A value of 10.80 microstrain/°C was obtained for cement paste, which is close to the reported value of 10 microstrain/°C. There was an almost linear relationship between coarse aggregate volume and CTE. He found that, for this aggregate type, the decrease in CTE was approximately 0.045 microstrain/°C per percent increase in coarse aggregate volume. This finding indicates that, for job control or a mix approval process, the coarse aggregate volume should be tightly controlled. He conducted a laboratory investigation to determine the coefficient of thermal expansion of typical concrete paving mixtures made with coarse aggregate from eight different sources in Michigan. The test results indicated that aggregate geology, specimen age at the time of testing, and the number of heating and cooling cycles that the specimen is subjected to have a statistically significant impact on the magnitude of measured CTE.

2.4. Use of design levels of CTE in the MEPDG

The MEPDG has established three levels of design. Level 3 is the lowest level of sophistication and should be used for facilities of relatively low importance and traffic levels. The input of CTE for a Level 3 design is an estimate based on historical data. This is considered to have a poor level of accuracy as PCC materials can be quite variable and Level 3 estimates have the greatest potential for error. Level 2 inputs for CTE are based on a weighted average of the constituent material quantities and their CTE values. Level 1 values for CTE are considered the most accurate as they are based on actual test results [13]. In this study, level 3 values have been used for CTE, elastic modulus and MOR in the absence of level 1 and level 2 values, which is a limitation of this study.

2.5. Simulation methodology

The sensitivity analysis of CTE on performance parameters of JPCP was performed by conducting the simulations in AASHTO Ware ME Pavement design software. The major design inputs including design life, traffic volume, climate, and etc. were considered constant as shown in Table 1. Simulations were conducted for various CTE values ranging from 7.2 to 14.4 micro-strains/°C to observe the effects of CTE on performance of JPCP. The effects of varying CTE values on transverse cracking, mean joint faulting and terminal IRI were analyzed on the predicted terminal values and also the CTE sensitivity to the performance over the entire pavement design life.

2.6. Results and discussion

2.6.1. Impact of varied CTE on predicted terminal performance

The simulation results were evaluated to determine the impact of CTE variability on the pavement performance parameters. Figs. 1–3 present the results of CTE variation on predicted terminal values of transverse cracking, IRI and joint faulting. It is evident from the results that as the CTE of concrete increases, the performance of JPCP is adversely affected. Transverse cracking, terminal IRI and joint faulting increases with increase in CTE values. The main reason for increase in the distresses is the increase in curling stresses due to increase in CTE of concrete. The slope of the curves for transverse cracking and terminal IRI is much steeper when CTE value goes above 11 micro-strain/°C and with further increase in CTE value, the pavement fails to meet the design performance criteria. The relation between CTE and terminal joint faulting is almost a straight line with joint faulting increasing with increase in CTE of concrete.

2.6.2. Impact of CTE variability over the pavement design life

The analysis of CTE variation on the performance parameters over the pavement design life was also conducted and the results are presented in Figs. 4–6. The threshold limit of transverse cracking was 15% and it is evident that when CTE value reaches 10.8 micro-strain/°C, the pavement crosses the threshold limit at the end of
design life and with further increase in CTE value the pavement fails to meet the threshold criteria in early life. A similar trend can be observed on the impact of CTE on pavement roughness as the pavement failed to meet the threshold criteria of IRI (2.72 m/km) near the end of design life with the CTE value of 11.7 micro-strain/°C and if CTE is further increased then pavement fails even earlier. The acceptable limit for joint faulting was 3.05 mm and the pavement fails to meet this limit when CTE of concrete increases from 11.7 micro-strain/°C. It is evident from these results that with increase in CTE of concrete the predicted distresses of JPCP also increases resulting in shorter pavement life.

3. Effects of elastic modulus on concrete pavement

3.1. Elastic modulus

Elastic modulus measures material stiffness and is a ratio of the applied stress to measured strain. It is measured...
according to ASTM C 469 with a concrete cylinder loaded in longitudinal compression at a relatively slow constant rate [14]. This type of test is very expensive due to the nature of the test so with extensive research, American Concrete Institute (ACI) developed a relation between elastic modulus and compressive strength of concrete (at 28 days), which gives quite satisfactory results for the elastic modulus values of concrete. Typical elastic modulus of normal strength Portland cement plain concrete ranges between 14 and 41 GPa ($2 \times 10^6$ and $6 \times 10^6$ psi).

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3.2. Importance of elastic modulus in JPCP design

Elastic modulus of concrete is an important variable in pavement design. It controls the overall slab deflections from traffic loading and slab curling stresses. Historically, in pavement applications, this value was not rigorously estimated. Typical value of 28.96 GPa (4.2 × 10^6 psi) was assumed during design of rigid pavement because it was perceived to have little effect. However, newer design methods such as the MEPDG have brought the importance of this parameter to the forefront. As elastic modulus is directly related to concrete strength so concrete with a higher elastic modulus behaves in a better way to deal with the curling and loading stresses as compared to the concrete with lower elastic modulus.

In general, the material characteristics affect the elastic modulus in the same manner as the compressive strength. However, elastic modulus is more sensitive to aggregate characteristics and volumes. The higher the modulus of elasticity of the aggregate, the higher will be the elastic modulus of the concrete. The shape of coarse aggregate particles and their surface characteristics also influence the value of modulus of elasticity of concrete.

3.3. Simulation of elastic modulus effects on JPCP

The simulation of the effects of elastic modulus of concrete on performance parameters of JPCP was conducted using MEPDG software. For this purpose, a constant CTE value of 9.9 micro-strain/°C for PCC layer was assumed and the rest of the design parameters were taken constant as given in Table 1. The performance characteristics of JPCP were obtained for different values of elastic modulus of concrete ranging from 24 to 35 GPa (3.5 × 10^6 to 5 × 10^6 psi).

3.4. Impact of elastic modulus variation on predicted terminal performance

The simulation results are shown in Figs. 7–9. After analyzing the simulation results, it is evident that as the elastic modulus of concrete increases, the terminal IRI decreases and in the same way the percentage of transverse cracking also decreases so the elastic modulus has a direct relation to pavement performance. In fact, elastic modulus is directly proportional to the compressive strength of concrete; this is also the reason that higher elastic modulus values give a better performance. However, there is no effect of elastic modulus variation on the terminal value of joint faulting.

3.5. Impact of elastic modulus variation over the pavement design life

The effects of varying elastic modulus on the pavement performance over the pavement design life were analyzed and the results are shown in Figs. 10 and 11. It is evident from the results that lower elastic modulus values give higher pavement roughness; however, the designed pavement satisfies the terminal IRI criteria for all the simulated elastic modulus values. The impact of elastic modulus on the transverse cracking is more pronounced and the designed pavement fails to satisfy the transverse cracking criteria at 26 years with elastic modulus value of 24.13 GPa (3.5 × 10^6 psi).

4. Effects of modulus of rupture on performance of JPCP

4.1. Modulus of rupture

The flexural strength or MOR of concrete defines the tensile capacity of concrete. Typically, concrete is not tested under direct tension because the test apparatus and the loading mechanism introduce secondary stresses that are not easy to compensate for in test results. Modulus of rupture can be determined as the maximum tensile strength at rupture of a simply supported concrete beam during a flexural test with third point loading, as standardized in ASTM C-78 [15]. This test measures the tensile capacity of the concrete in bending or flexure. Modulus of rupture is influenced by mix design parameters including water to cement ratio, cement type, cement content, and aggregate properties (aggregate type, maximum size, gradation, and surface texture).

4.2. Importance of modulus of rupture in concrete pavement

Modulus of rupture of a fully supported slab is far greater than the flexural strength of a simply supported
beam. It is the basis for estimating flexural fatigue in concrete. In MEPDG, the damage calculated for the estimation of transverse cracking is a function of the flexural strength of the concrete. A true estimation of modulus of rupture would improve the accuracy of cracking prediction. Although modulus of rupture is an important parameter in evaluating the design of rigid pavement, it was not given due importance in the past. With the advent of MEPDG, a lot of emphasis has been given to accurate

Fig. 9. Impact of elastic modulus on terminal joint faulting.

Fig. 10. Impact of elastic modulus ($E_c$) on IRI over the pavement life.

Fig. 11. Impact of elastic modulus ($E_c$) on cracking over the pavement life.

Fig. 12. Effects of modulus of rupture on terminal IRI.

Fig. 13. Effects of modulus of rupture on terminal transverse cracking.
determination of modulus of rupture and its use in design of rigid pavement.

4.3. Simulation of effects of modulus of rupture on JPCP

To evaluate the effects of modulus of rupture on performance of concrete pavements, simulations were conducted with different values of modulus of rupture ranging from 4 to 5.7 MPa (580 to 830 psi) while keeping a constant CTE value of 9.9 micro-strain/°C (5.5 micro-strain/°F) for PCC layer. The rest of the design parameters were taken as given in Table 1. The effects on the performance parameters were analyzed to contrast the effects of modulus of rupture on pavement design.

Fig. 14. Effects of modulus of rupture on terminal joint faulting.

Fig. 15. Impact of modulus of rupture on IRI over the pavement life.

Fig. 16. Impact of modulus of rupture on transverse cracking over the pavement life.
4.4. Impact of modulus of rupture variation on predicted terminal performance

The results for impact of modulus of rupture on predicted terminal values of performance indicators have been plotted and shown in Figs. 12–14. After analyzing the simulation results, it is clear that as the modulus of rupture of concrete increases, the terminal IRI decreases and in the same way the percentage of transverse cracking also decreases. In fact, a higher modulus of rupture values gives a better performance. However, it can be observed that there is no effect of modulus of rupture variation on joint faulting.

4.5. Effects of modulus of rupture variation over the pavement design life

The simulation results were evaluated for the pavement performance including pavement roughness and transverse cracking over the design life of the pavement and are shown in Figs. 15 and 16. It can be inferred from the analysis that the change in MOR value of concrete affects the pavement roughness but the IRI values remains under the threshold limit. However, MOR has more significant effect on the cracking distress and with MOR value of 4.02 MPa, the pavement fails to satisfy the transverse cracking criteria at the pavement age of 26 years. In addition, the cracking distress increases rapidly when MOR value slides below 4.5 MPa.

5. Conclusion

The results obtained from the simulations confirmed the findings from the literature review regarding effects of mechanical and thermal properties of concrete on performance and service life of JPCP. With an increase in CTE of concrete, the performance of JPCP is adversely affected, due to higher curling stresses. Specifically, CTE above 10 micro-strain/°C should be avoided as it may result in early failure of the pavement. Concrete strength increases with increase in elastic modulus and modulus of rupture values which results in an improved performance of concrete pavement. These material properties have significant impact on transverse cracking, slight effect on pavement roughness and no effect on joint faulting as observed from the simulation results.

References