DURABLE PAVEMENT WITH ECC

Shunzhi Qian (1, 2) and V. C. Li (1)

(1) The Advanced Civil Engineering Materials Research Laboratory, Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, Michigan, 48109, USA

(2) Microlab, Faculty of Civil Engineering and Geosciences, Delft University of Technology, 2600 GA, Delft, The Netherlands

Abstract

While jointed plain concrete pavement (JPCP) has been extensively used in highway construction due to the wide availability of concrete materials, brittle fracture failure due to repeated loadings remains the major limitation to its durability and service life. The use of ductile concrete named Engineered Cementitious Composite (ECC) as an alternate pavement material should arrest such failure mode and greatly enhance its long term durability performance. In this paper, we introduce and demonstrate this concept via experimental study of the fatigue performance of ECC beam and FEM analysis of pavement structures. The ECC specimens totally eliminate the single fracture mode in concrete by developing extensive micro-cracks under flexural fatigue loading, in addition to a much enhanced modulus of rupture compared to controlled concrete specimen. Based on FEM analysis of the ECC pavement and fatigue performance of the ECC beam, a simplified design chart for ECC pavement is presented to facilitate the implementation of the proposed technology.

Keywords: Jointed plain concrete pavement (JPCP), Brittle fracture failure, Engineered Cementitious Composites (ECC), Micro-cracks, Durability and service life.

1. INTRODUCTION

From the first concrete pavement built in Ohio in 1893 [1], it has become one of the major pavement type around the world due to the wide availability, good workability of concrete materials and high load carrying capacity of the pavement. Nevertheless, concrete pavements are still prone to fail by brittle fracture due to fatigue loading (Fig. 1), which greatly limits its long term durability and service life. Even though significant efforts has been made to alleviate the fatigue fracture problem, including flexural strength enhancement, thickness increases, and fiber reinforced concrete [2], the problem still persists due to the inherent brittleness of concrete material. Therefore, it is conceived that a ductile concrete, such as Engineered Cementitious Composites (ECC), may be able to prevent such failure mode and result in a long lasting pavement.

Figure 1: Fractured concrete pavement slab due to repeated loading [3]

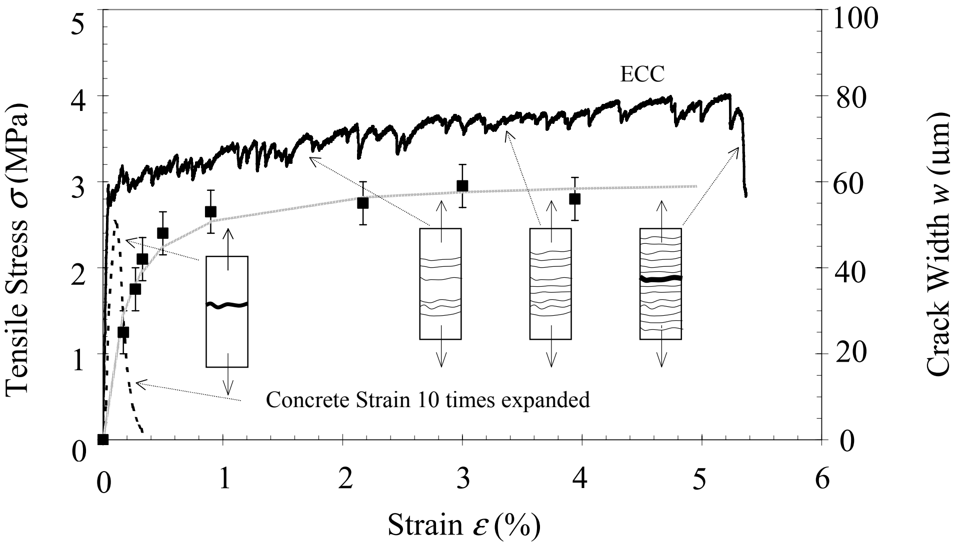

Figure 2: Typical tensile stress-strain curve of ECC

Engineered Cementitious Composites is a special type of fiber reinforced cementitious material, characterized by superior tensile ductility via multiple micro-cracking under tension. ECC has a tensile strain capacity in the range of 3-5% (300-500 times that of normal concrete or fiber reinforced concrete FRC) [4,5]. A typical tensile stress-strain curve of ECC is shown in Fig. 2, along with crack width development at different loading stages. The tensile strain-hardening behavior, i.e. increasing load capacity with increasing straining without localizing into a fracture plane, distinguishes ECC from FRC. FRC shows tension-softening after first cracking – i.e. a decreasing load capacity with increasing opening of a localized fracture. It is particularly interesting to note that even under fatigue loading condition, ECC has revealed significant multiple cracking as opposed to single fracture in normal concrete [6]. This observation suggests that it is feasible to use ECC as pavement material to address brittle fracture failure commonly observed in concrete pavement.

Overall research framework proposed by Qian [7] for ECC pavement overlay will be adopted in this investigation for pavement application with ECC, i.e., derivation of pavement thickness – fatigue life relation (h-N relation) via integration of flexural fatigue test (in the form of fatigue stress – fatigue life (σ-N) relation) and FEM analysis results (in the form of critical stress – pavement thickness (σ-h) relation), as shown in Fig. 3. In the following sections, first the flexural fatigue test results will be presented, followed by FEM analysis of pavement structures. By integrating both the flexural fatigue test with FEM analysis results, a simplified design chart (h-N relation) for ECC pavement will be developed for practical design.

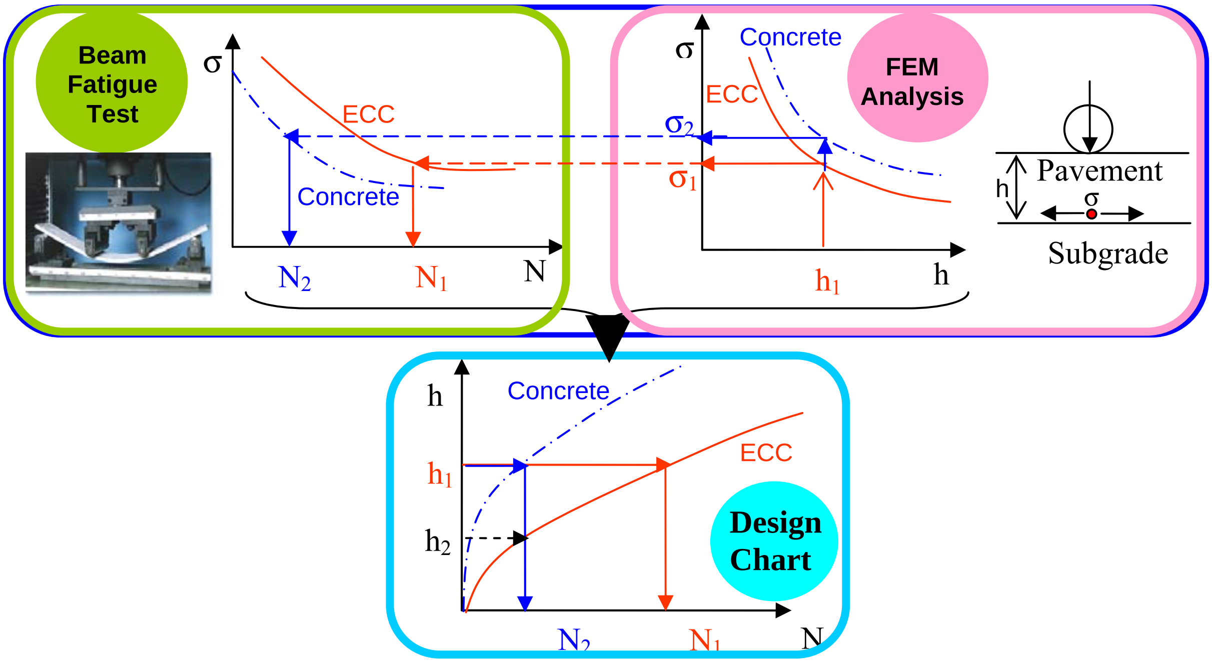

Figure 3: Integration of FEM analysis and material fatigue test result

2. FLEXURAL FATIGUE TEST

The ECC mixture investigated in this study are revealed in Table 1. In addition to ECC, one concrete from Oh [8] is also listed for reference, which has a MOR typically used in pavement [2]. Uni-axial tensile, compressive and flexural properties are determined for the ECC. Unaxial tensile testing used coupon plate specimens with dimensions of 304.8 x 76.2 x 12.7 mm [9]. The compressive properties were obtained from cylinder specimens (75 mm in diameter by 150 mm in height) [9].

The flexural specimens have a dimension of 356mm (length), 50mm (height) and 76 mm (depth), with a span between two supports of 305mm. Four point bending test was conducted at a constant moment span length of 102mm The MOR (flexural strength) was determined using elastic beam theory. The monotonic test was conducted under displacement control at a rate of 0.5mm (0.02in.) per minute, considering the very large deflection capacity of ECC due to its high tensile ductility.

Once the flexural strength was obtained from monotonic test, the fatigue loading was applied. Fatigue cycles began using load control with sinusoidal waveform at a frequency of 8 Hz. The fatigue load ratio (maximum flexural stress, σ_{max} over MOR) was chosen to be 0.7, 0.8 and 0.9. The minimum flexural stress, σ_{min}, was kept to 20% of the maximum flexural stress. The fatigue life recorded for a given maximum flexural stress was then used to construct the σ-N relation.

Table 1: Material properties and mix proportion of ECC and concrete (Mix by weight (fiber by volume))

Material	ε_{tu} (%)	f_{tu} (MPa)	f_c' (MPa)	MOR (MPa)	C	S	CA	FA	W	SP	PVA Fiber
ECC	3.7 ±0.4	4.9± 0.1	37.5 ±1.7	11.1 ±0.6	1.0	1.4	0	2.8	0.99	0.016	0.02
Concrete [8]	0.01	-	27.0	4.6	-	-	-	-	-	-	-

(ε_{tu}: tensile strain capacity; f_{tu}: ultimate tensile strength; f_c': compressive strength; MOR: modulus of rupture (flexural strength); C: cement; S: sand; CA: coarse aggregate; FA: fly ash; W: water; SP: superplasticizer; PVA fiber: KURALON K-II REC15)

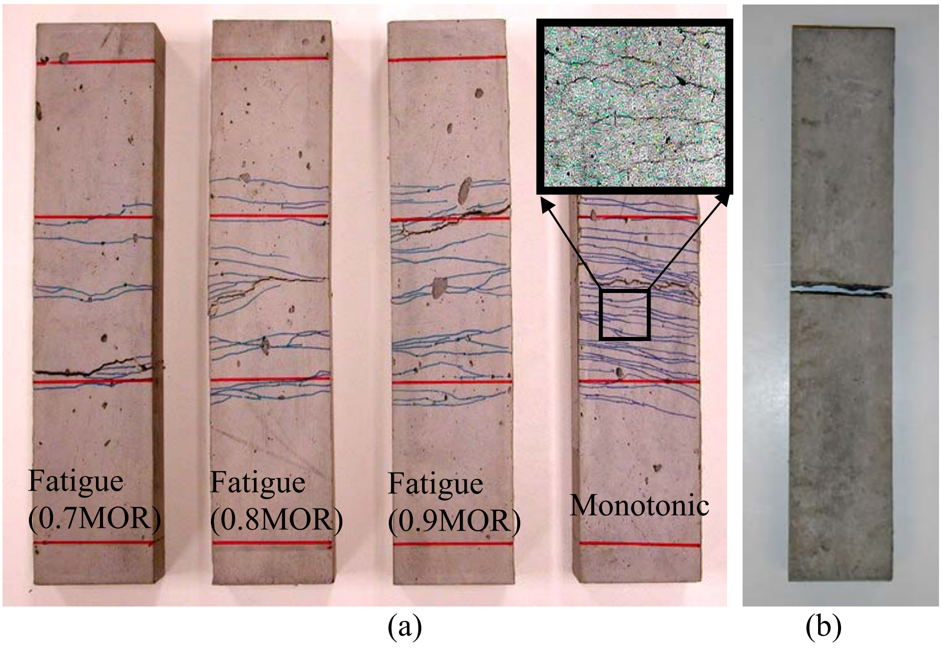

Figure 4: Crack pattern for (a) ECC specimens under flexural monotonic and fatigue loading; (b) concrete specimen (The microcracks shown in (a) are marked by magic ink pen for clarity while actual microcracks before marking are shown in close-up frame)

ECC reveal multiple cracking behavior both under monotonic and fatigue loading while concrete always fails by sudden fracture localization, as shown in Fig. 5. As the fatigue stress level decrease, the number of microcracks also decrease in ECC. This observation suggests that when the fatigue load level decrease, it is more difficult for ECC beam to reach saturated multiple cracking since the corresponding tensile stress at the bottom of the beam may be very close to the cracking strength.

Under fatigue loading condition, ECC show great enhancement in terms of fatigue stress – fatigue life relation when compared with concrete because of high tensile ductility. The fatigue stress – fatigue life relation (σ-N relation) is shown in Fig. 5, where concrete result is from Oh [8]. As can be clearly seen, under same fatigue stress level, the fatigue life of ECC may be at least 9 orders of magnitude higher when compared with that of concrete. It is expected therefore, that the introduction of ECC will greatly enhance the pavement service life. The S-N regression equations are also shown in Fig. 5.

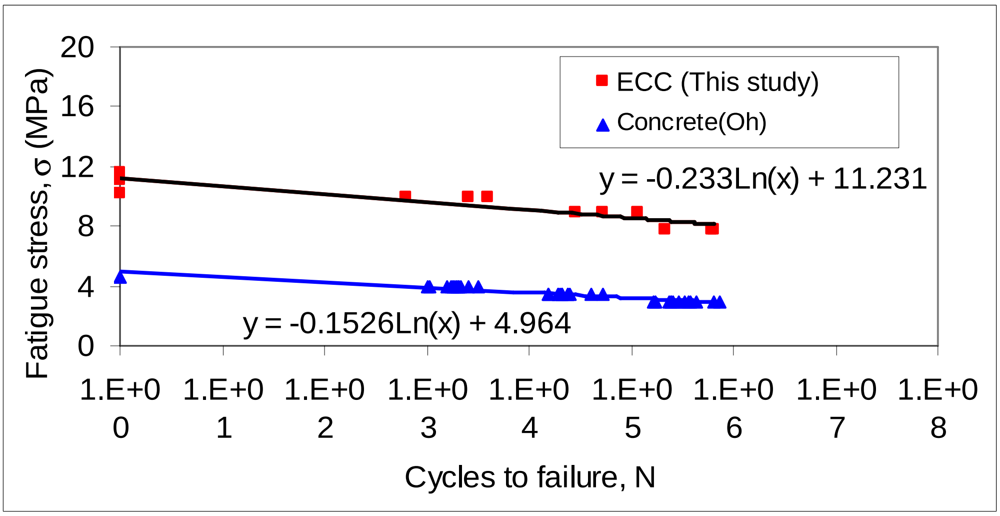

Figure 5: Flexural fatigue stress with fatigue life relation for ECC & concrete beam

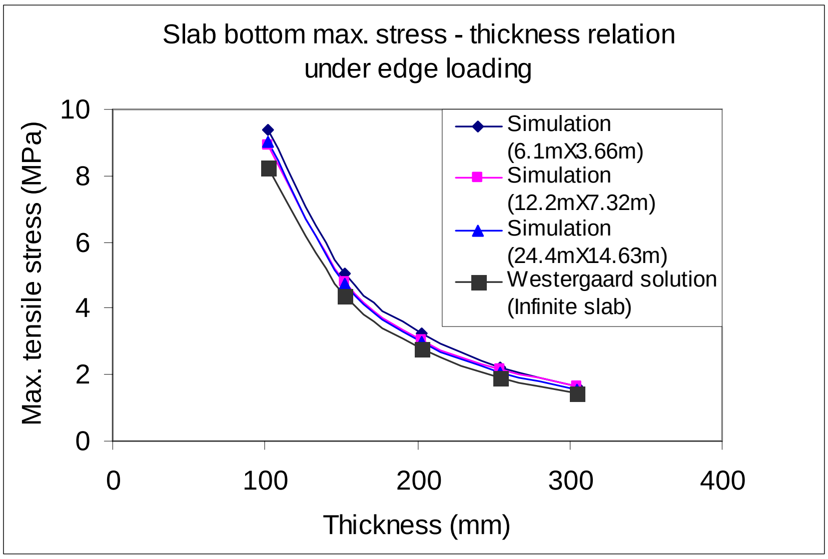

Figure 6: Comparison of simulation results with Westergaard solution under edge loading in terms of slab bottom maximum tensile stress with thickness relation

3. FEM MODEL AND ANALYSIS

An FEM program, JSLAB-2004 [10] was used for the characterization of critical tensile stress in the pavement slab under edge loading. To verify the validity of modeling, a simple pavement slab was simulated to compare the computed response with classic Westergaard solution under edge loading. The FEM results compared favorably with Westergaard solution, as can be seen in Fig. 6, where the slab size in simulation is increased to approach Westergaard solution scenario (infinite slab). More detailed description can be found in Qian [6].

Detailed FEM model for pavement slab is shown in Fig. 7. Standard equivalent single axle load (ESAL: 80KN) was applied near the edge of the pavement slab to maximize the edge tensile stress at the bottom of the slab. The pavement slab has a dimension of 6.1 by 3.6 m for both concrete and ECC cases for convenience. In case of ECC, it is very likely a greatly extended joint spacing, if not jointless, will be used in actual pavement. Therefore, it will be conservative for the case of ECC pavement to use a slab dimension the same as that of concrete in the FEM analysis.

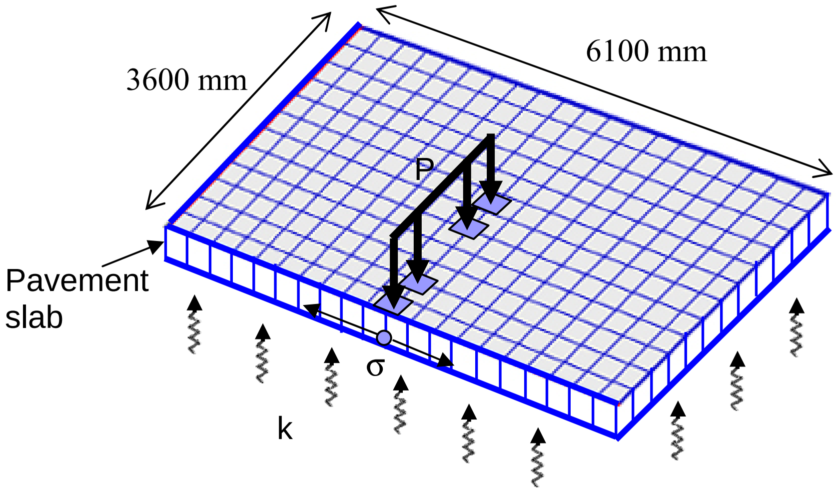

Figure 7: Finite slab under one ESAL loading for FEM analysis

The FEM analysis results are shown in Figs. 8 and 9 in the form of maximum tensile stress - pavement thickness relation with varying modulus of elasticity and modulus of subgrade reaction. As expected, the maximum tensile stress decreased with the increased pavement thickness in both figures. In Fig. 8, the ECC pavement induces smaller tensile stress due to its lower modulus of elasticity compared with concrete cases, confirming the results in the case of ECC overlay analysis [7]. Fig. 9 reveals the influence of increased subgrade stiffness (modulus of subgrade reaction) on the reduction of maximum tensile stress, which confirms the importance of high quality subgrade on the improvement of pavement performance.

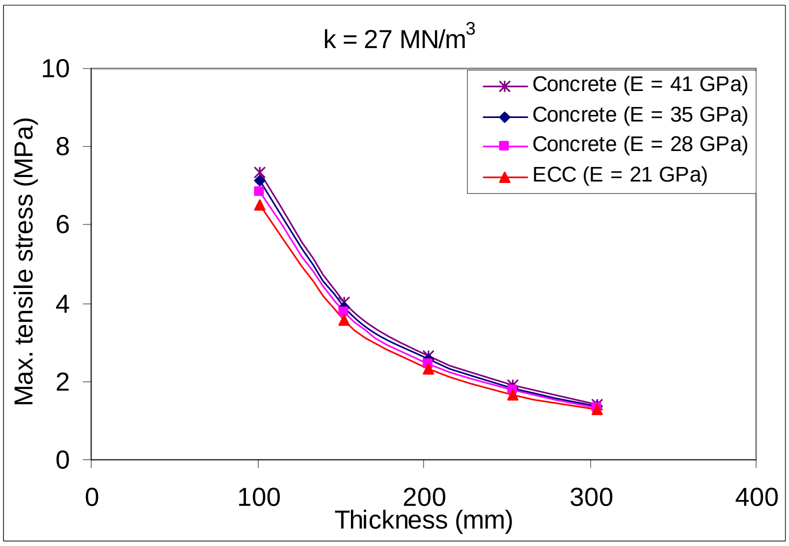

Figure 8: Maximum tensile stress - pavement thickness relation with varying modulus of elasticity

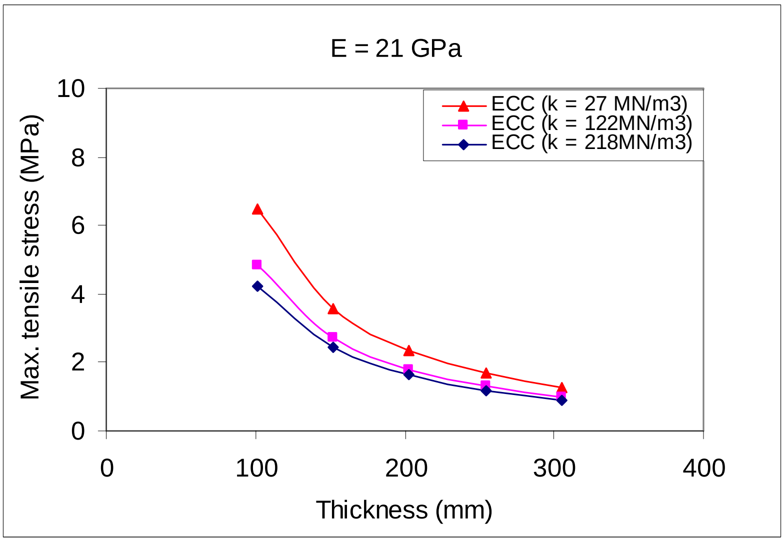

Figure 9: Maximum tensile stress - pavement thickness relation with varying modulus of subgrade reaction

4. INTEGRATION OF EXPERIMENTAL TEST AND FEM ANALYSIS

Fatigue test results and FEM analysis results were integrated into pavement thickness – fatigue life relation, as shown in Fig. 10. The modulus of elasticity for concrete and ECC is 28 and 21 GPa and the modulus of subgrade reaction for all cases is 27 MN/m^3. As expected the required thickness for ECC pavement is much thinner compared with that of concrete pavement when same fatigue life is assumed. The thickness of concrete pavement increases from 1.8 to 2.7 times that of the ECC pavement given the same fatigue life.

While maintaining advantage of ECC pavement in life cycle cost is very important, the initial material cost for the construction project is also critical in decision-making. It would be much easier for ECC pavement to be accepted by the decision-maker if the cost is lower from both initial material and life cycle viewpoint. Only the initial material cost will be briefly discussed in this paper. The initial material cost of ECC pavement will be lower compared with concrete pavement if the thickness ratio between concrete and ECC pavement is larger than their unit material cost ratio (e.g. \$ per m^3, ranging from 2-3 depending on composition [11]).

The pavement thickness/thickness ratio with cycles to failure relation is shown in Fig. 10, where thickness ratio is the ratio of concrete pavement over ECC pavement assuming same fatigue life. As can be easily seen from the figure, once the fatigue life exceeds $1x10^5$ the ECC pavement will be more favorable even in the initial material cost, assuming material unit cost ratio is 2. The life cycle cost of ECC pavement will be very likely lower due to jointless/larger joint spacing and less maintenance potentially involved.

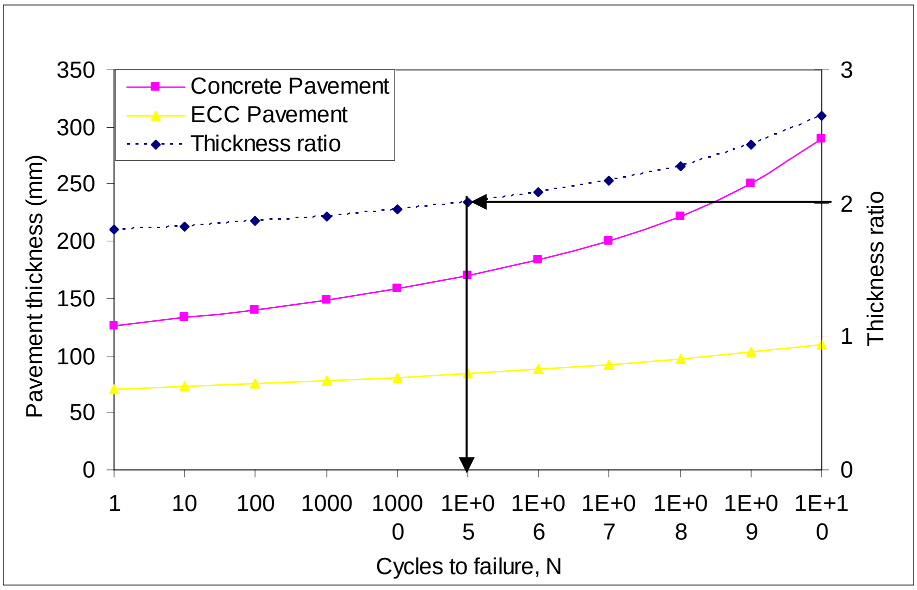

Figure 10: Pavement thickness and thickness ratio with cycles to failure relation (same cycles to failure is assumed for both pavements)

5. CONCLUSIONS

This paper investigated the influence of ductile concrete material fatigue resistance on the rigid pavement performance via the integration of flexural fatigue experiments and FEM analysis of pavement structures. The overall findings suggest that ECC may serve as an alternative material technology to effectively enhance the durability performance of rigid pavement and service life. The following specific conclusions can be drawn:

– The single fracture induced by fatigue loading in concrete pavement can be diffused by micro-cracking process in the ECC pavement due to high tensile ductility of ECC.
– ECC is a promising alternative material for a rigid pavement application due to its superior fatigue performance. It was found that ECC can reduce the thickness by more than 50% compared with that of concrete pavement given same service life.
– A design chart for ECC pavement is derived based on integration of fatigue test results and FEM analysis. The design chart is expected to facilitate the decision

maker for pavement investment at the early planning stage and can also be used for life cycle assessment and cost analysis.

ACKNOWLEDGMENTS

The authors would like to acknowledge the financial support from NSF MUSES programs (CMS-0223971, CMS-0329416), Dr. Mike Lepech for helpful discussions and Dr. Weijun Wang at Federal Highway Administration for help regarding the use of the J-SLAB software.

REFERENCES

[1] Fitch, M., "Bellefontaine, Ohio: Home of America's Oldest Concrete Pavement," Summer 1996, pp. 4-6; Ohio T2 Center, Ohio State University.
[2] Huang, Y. H., Pavement Analysis and Design, 2nd edition, Pearson Education Inc, 2004, Upper Saddle River, NJ 07458.
[3] Caltrans, (California Department of Transportation), Pavement tech notes interim, PCC pavement rehabilitation guidelines, revised July 28, 2004.
[4] Li, V.C. and T. Kanda, 1998, "Engineered Cementitious Composites for Structural Applications", Innovations Forum in ASCE, J. Materials in Civil Engineering, 66-69.
[5] Li, V. C., Wang, S. and Wu, C., 2001, "Tensile Strain-hardening Behavior of PVA-ECC", ACI Materials Journal, 98(6) 483-492.
[6] Matsumoto, T., P. Suthiwarapirak, and T. Kanda, "Mechanisms of Multiple Cracking and Fracture of DFRCCs under Fatigue Flexure," Proceedings of the JCI International Workshop on Ductile Fiber Reinforced Cementitious Composites (DFRCC) - Application and Evaluation (DRFCC-2002), Takayama, Japan, Oct. 2002, pp. 259-268.
[7] Qian, S., Influence of Concrete Material Tensile Ductility on the Behavior of High Stress Concentration Zones, PhD dissertation, 2007, University of Michigan.
[8] Oh, B. H., Fatigue life distributions of concrete for various stress levels, ACI material Journal, v88, no.2, 1991, pp 122-128.
[9] Wang, S. and Li, V. C., Engineered Cementitious Composites with High-volume Fly Ash, ACI Material Journal, Vol 104, No. 3, May-June, 2007, pp. 233-241.
[10] FHWA, JSLAB-2004 User's Manual (Upgrade Supplement), Prepared by Galaxy Scientific Co. for Federal Highway Administration, 2004, 49 p.
[11] Lepech, M. D., A Paradigm For Integrated Structures And Materials Design For Sustainable Transportation Infrastructure, Ph.D. Thesis, Univ of Michigan, Ann Arbor, 2006.