A TECHNICAL STUDY ON MIX DESIGN FOR PAVEMENT OVERLAYS FOR SUSTAINABLE DEVELOPMENT

PONNOJU SAI KRISHNA* , B.SREENU**
*P.G. Scholar (M. Tech), Dept. of CIVIL, Varaprasad Reddy Institute of Technology, Sattenapalli - 522438. Email Id: ponnojusai123@gmail.com
**Assistant Professor, Dept. of CIVIL, Varaprasad Reddy Institute of Technology, Sattenapalli - 522438. Email Id: sreenubhuvanagiri@gmail.com

Abstract—Contributing nearly 5% of global anthropogenic greenhouse emissions through cement production alone, the concrete industry is a major contributor to global climate change. Automobiles and trucks that use concrete transportation infrastructure release another 30% of anthropogenic greenhouse emissions. Along with these atmospheric emissions, the construction, repair, and rehabilitation of concrete pavements rely on the production and flow of large quantities of concrete material and its constituents. To reduce environmental impact and improve the sustainability of pavement overlay systems, a class of materials called Engineered Cementitious Composites (ECC) is introduced to construct more sustainable, durable rigid pavement overlays. ECC overlays are designed to enhance sustainability in two ways. First, "greener" ECC materials incorporate high volumes of industrial waste to reduce the environmental impacts of material production. Fundamental micromechanics carefully guide this green material design to maintain pseudo-strain hardening material behavior under tension overlays, significant sustainability improvements have been modeled. These improvements are quantitatively measured using life cycle cost and life cycle assessment techniques.

1. INTRODUCTION

Unsustainable material production for concrete pavements begins with the production of Portland cement. The mining, calcining, and grinding of Portland cement contributes nearly 5% of global anthropogenic greenhouse emissions, making the cement and concrete industries a major contributor to global climate change. Following this initial construction, poor maintenance of concrete pavements can lead to excessive deterioration and associated repair needs. As recently as 2009, the American Society of Civil Engineers assigned grades of C and D to America's bridges and roads, respectively. This deteriorated state can lead to repeating cycles of short-term repair scenarios, which result in increased material consumption of repair materials and fuels.

OBJECTIVES AND SCOPE OF THE PRESENT STUDY

The broad objective of this study is "analysis and performance evaluation of Mix Design Overlaying subjected to various traffic and climatic conditions subjected to Indian scenario". The specific objectives and scope of the present study can be summarized as:

- To review and identify the gap in the literature for the analysis and performance evaluation of Mix Design.
- To investigate the structural adequacy of the existing flexible/HMA pavement using Benkelman Beam Deflection (BBD) and to carry out various soil investigations.
- To develop a three dimensional Finite Element non-linear model of conventional whitetopping for unbonded condition and linear model of UTW for bonded condition by considering static wheel loading and temperature loading.
- To validate the FE model by computing stresses and deflections at edge, corner and interior loading positions and comparing the same by conducting FWD/BBD test and using closed form formulae.
- To evaluate the performance of whitetopping for Indian traffic and climatic conditions.
- To develop an alternative tool to FWD test for measuring LTE across transverse joints and also developing correlation between Benkelman Beam and FWD deflection for conventional whitetopping.
- To carry out life cycle cost analysis (LCCA) of conventional whitetopping and UTW to study their cost effectiveness.

Keeping in view these objectives and scope of work, available literature has been critically reviewed and scope of the present work has been identified

2. LITERATURE SURVEY

A general guideline for whitetopping construction was available as early as 1989 from the Portland Cement Association (PCA) and the American Concrete Pavement Association (PCA, 1989; ACPA, 1991; ACPA, 1997). However, the design thickness methodology and guideline was not available until the development of the PCA, UTW design procedure (Mack et al., 1997; ACPA, 1997; Wu et al., 1998). This approach assumed a partial bond between the PCC overlay and the underlying HMA, instead of "fully bonded" or "completely unbonded" as in the previous design methods. This was followed by the state of Colorado and PCA investigation on whitetopping pavements' behaviour under heavy traffic (Tarr et al., 1998). The state of Colorado and PCA study is similar to the earlier PCA study on UTW. The state of Colorado and PCA study found that there are performance differences between UTW and TWT. Based on the findings, a procedure, similar to PCA, PCC thickness design procedure (PCA, 1984) was developed for thin whitetopping pavements.

3. Some of the more advanced procedures that have been recently developed include the modified American Concrete Pavement Association (ACPA) procedure (Riley et al., 2005) and the Total Systems Analysis Approach (The Transtec Group, 2005) for design of whitetopping pavements. Different approaches are followed in developing these methods for design of whitetopping. The popular and widely used methods of whitetopping design are Indian Road Congress (IRC:58-2002, IRC: SP:76-2008) Method, Portland Cement Association (PCA,1984) method, Colorado TWT design procedure, American Association of State Highway and Transportation Officials (AASHTO, 1993) Method. The Basic features of these design methods are summarised in the following sections.

3. INDIAN ROAD CONGRESS (IRC:58-2002 AND IRC:SP:76-2008) METHOD

The design principle adopted for conventional whitetopping is similar to those of normal rigid pavements as provided in IRC: 58-2002 "Guidelines for the design of plain jointed rigid pavements for highways". The IRC:58-2002 approach is somewhat similar to that of PCA method (1984) of thickness design of conventional whitetopping. Wheel load stresses are computed based on the works of Westergaard and Pickett and Ray. Fatigue cracking is considered as the main mode of distress. Linear temperature differential is assumed for calculation of curling stresses based on Bradbury's work. Algebraic summation of the wheel load stress and curling stress is considered to be the critical combination for thickness design. The thickness of overlay is determined assuming the flexible pavement as a base. The modulus of subgrade reaction (k value) of the pavement is determined and the overlay thickness is calculated.

- There are a number of procedures for design of whitetopping. Existing procedures include the AASHTO Guide (AASHTO, 1993); the state of Colorado procedure (Sheehan et al., 2004; Tarr et al.,1998); the Portland Cement Association (PCA)/American Concrete Pavement Association (ACPA) method (Wu et al., 1998); the state of New Jersey method (Nenad, 1998); the modified ACPA approach (Riley et al., 2005); the state of Illinois method (Roesler et al., 2008); and the state of Texas method (Chul et al., 2008). Among these, AASHTO, Colorado, and Texas provide design procedures which can be used for designing TWT, while the rest are for procedures for UTW. Recently, MnDOT (2010) has developed a design technique for TWT. A number of design guidelines are available for design of whitetopping. These guidelines are based on traffic and environmental conditions that are country /region specific. There are number of existing design procedures that have been used for whitetopping design. The different design procedures have been identified in the literature, including those developed by the states of Colorado (Tarr et al., 1998; Sheehan et al., 2004) and New Jersey (SWK Pavement Engineering, 1998), the Portland Cement Association (Wu et al., 1998) and the American Association of State Highway and Transportation Officials (AASHTO), or the American Concrete Pavement Association method (ACPA, 1998).
    - Budget constraints are forcing many state transportation agencies to look at pavement preservation or rehabilitation rather than reconstruction to ensure pavements are in serviceable condition. Major rehabilitation is undertaken when the pavement is in need of structural improvement. Portland cement concrete overlays also called whitetopping are used as a rehabilitation technique for both existing concrete and asphalt pavements. Different studies conducted for understanding the interface characteristics, load transfer behaviour, performance evaluation and modeling of different types of overlays also have contributed to the improvement in the whitetopping design methods not limited only to the United States (U.S.) only but also in other countries including Belgium, Sweden, Canada, Mexico, Brazil, the Republic of South Korea, Japan, France, Austria, and the Netherlands who have undertaken recent projects with whitetopping (Rasmussen and Rozycki, 2004). Also, India has undertaken some experimental sections of whitetopping. In this chapter, a brief review of literature has been presented on the classification, design, modeling and performance evaluation of whitetopping. Salient features of literature available on the subject matter have been considered for identifying the scope of present work. accurately represent the effects of bending in structures.

4. PAVEMENT APPLICATIONS

In the last decade, a new type of composite called Engineered Cementitious Composite (ECC) has been developed. ECC is a special type of high performance fiber-reinforced cementitious composite featuring high ductility and damage tolerance under mechanical loading, including tensile and shear loadings [2–4]. By employing micromechanics-based material optimization, tensile strain capacity in excess of 3% under uniaxial tensile loading can be attained with only 2% polyvinyl alcohol (PVA) fiber content by volume [2,5,6]. Unlike most vinyl polymers, PVA is not prepared by polymerization of the corresponding monomer. The monomer, vinyl alcohol, is unstable with respect to acetaldehyde. PVA instead is prepared by first polymerizing vinyl acetate, and the resulting polyvinylacetate is converted to the PVA.

TEST PROCEDURES

Three prismatic samples of 355 mm × 50 mm × 76 mm were prepared to measure the flexural strength of ECC (Modulus of rupture), for ages 28 and 56 days by performing four-point bending test under displacement control condition at a loading rate of 0.005 mm/s on a closed-loop servo-controlled loading system. The span length of flexural loading was 304.8 mm with a 101.6 mm center span length. During the flexural tests, the load and the mid-span deflection were recorded on a computerized data recording system. The schematic of the test setup with a photo is presented in Figure 1. Flexural strength of the specimens was calculated in accordance with ASTM C 78 [27].

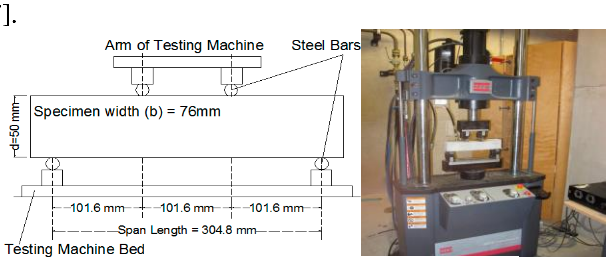


Figure-2. Four point bending test setup.

Two approaches were adopted for investigating the ECC performance under fatigue flexural test: the first was applying different fatigue stress levels and the second was applying different fatigue cyclic loading. Accordingly, four prismatic samples of 355 mm × 50 mm × 76 mm were prepared for the age of 28 days. The four-point bending test was conducted under both static and fatigue loading. Two out of four samples were prepared for static loading tests as control specimens which were carried out under displacement control conditions, while the other two samples were prepared for fatigue loading tests which were performed under load control conditions. Specimens were simply supported on a span of 304.8 mm and subjected to two-point loads at one-third of the span as shown in Figure 1.

In the first approach, static flexural tests were conducted before fatigue flexural tests at the constant rate of 0.005 mm/s. The static flexural strengths were determined by averaging the flexural strength results of ECC control specimens. Based on their static flexural averages, the different maximum fatigue stress levels were determined as 40%, 55% and 70% and the tests were conducted at 50,000 cycles and 4 Hz cyclic loading rate. In the second approach, 55% of fatigue stress level value was fixed and tests were conducted at different fatigue cycles namely 200,000 cycles, 300,000 cycles and 1,000,000 cycles at the same 4 Hz cyclic loading rate as well.

Fatigue flexural tests were performed under load control conditions. The ratio between minimum and maximum flexural stress was set equal to 0.30 for all specimens in order to avoid any impact and slip of specimens during testing. At the first cycle of each specimen, load was gradually applied to the maximum stress level at 0.50 kN/min static loading rate in order to avoid any sudden collapse in the specimen. The cyclic fatigue loading was then applied. The fatigue testing technique mentioned above was adopted in accordance with Suthiwarapirak et al. [28]. During the fatigue flexural tests, the mid-span deflection evolutions were recorded on data sheet and at the end of the fatigue flexural tests; static flexural tests were conducted on the fatigued ECC specimens to calculate the fatigue residual values for both strength and mid-span deflection.

To evaluate the performance of ECC under typical transportation-related mechanical and environmental loads, durability tests and long-term performance studies on ECC materials have been conducted by the authors and other researchers. These tests include restrained shrinkage tests, fatigue and bonding tests, freeze thaw exposure, wearing/abrasion tests, and accelerated environmental tests. Additionally, the long-term strain capacity and early age strength development of ECC have been investigated. These studies confirm that ECC will successfully perform as a rigid pavement overlay material for highway applications.

RESTRAINED SHRINKAGE

To examine the restrained shrinkage behavior of ECC, ring tests (AASHTO PP-34) were carried out for both ECC and normal Portland cement concrete. Due to the high cement content of ECC, significantly higher free shrinkage deformation is exhibited, compared to normal concrete [5]. However, restrained shrinkage tests show that although hygral deformation may be higher, crack widths in ECC remain below 50mm (50% relative humidity, RH, for 100 days), compared to concrete crack widths of approximately

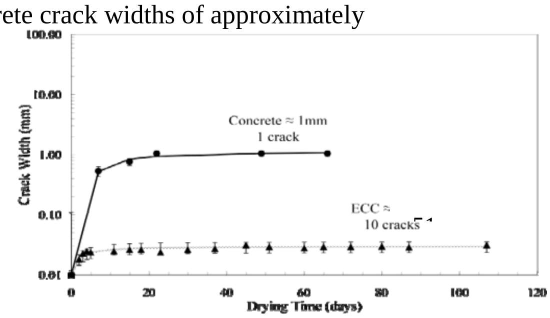


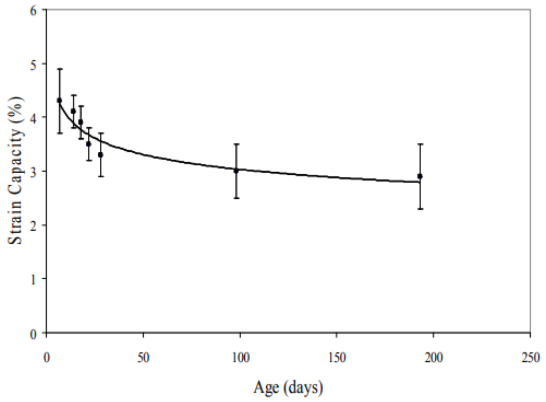
Figure-3. Crack Width Development as a Function of Drying Time (RH=50%) [5].

1mm (Fig. 4). This is achieved through the microcracking of ECC, allowing the shrinkage deformation to be distributed over a large number of small cracks, while all shrinkage deformation in concrete localizes at a single crack. Further, the formation of shrinkage cracks at ECC/concrete interfaces is prevented by lower interfacial stresses due to the large deformability of ECC.

FATIGUE TESTING AND OVERLAY BOND CHARACTERISTICS

The fatigue characteristics of ECC were investigated to assess the performance in high fatigue scenarios, such as pavement overlays. Both ECC/concrete and concrete/concrete overlay specimens were tested in flexural fatigue [10]. In overlay applications, reflective crack propagation through the overlay is a common mode of failure. This reflective cracking reduces load capacity and result in flexural fatigue. Tests show the flexural capacity of ECC overlaid on a concrete substrate was double that of specimens with concrete overlaid on a concrete substrate. The deformability of ECC/concrete specimens was also increased while fatigue life was extended by several orders of magnitude over concrete/concrete specimens. Further, the microcracking deformation mechanism of ECC eliminates reflective crack localization.

In addition to fatigue performance and crack resistance, the bond characteristics of ECC/concrete interfaces have been investigated. Using ECC as an overlay material, the delamination and accompanying deterioration processes, typically seen in many concrete/concrete applications were not seen. Through a unique kinking-and-trapping crack formation process, both the load capacity and energy absorption of the ECC/concrete overlay was increased over concrete/concrete systems. In this mechanism, cracks propagate slightly along the bonding interface but are then directed into the ECC overlay and immediately arrested by the high ECC toughness (34kJ/m2 [11]). This kinking-and-trapping process is repeated until the ECC ultimately fails in flexure, unrelated to interfacial debonding. Additionally, tests have been performed to investigate the influence of surface preparation on bonding. These tests show that regardless of a smooth or roughened interface, the bond performance of an ECC/concrete overlay is superior to that of a concrete/concrete overlay [12].



Figue-4. Tensile Strain Capacity Development of ECC Material [15].

FREEZE THAW

Freeze thaw testing in accordance with ASTM C666A have been performed on companion series of Poly-vinyl-alcohol (PVA) fiber reinforced ECC and normal plain concrete specimens were exposed to frost cycles. In addition to dynamic modulus testing of prism specimens as outlined in C666A, a series of ECC tensile specimens were also subjected to frost cycles. This testing series evaluated the effect of frost conditions on composite strain capacity. Results from these tensile specimens were compared to tensile coupons of identical age cured in water at 22ºC.

Testing of prism specimens was conducted over 14 weeks. The ECC specimens survived the entire test duration of 300 cycles with no degradation of dynamic modulus. This performance results in a durability factor of 100 for ECC specimens, as computed according to ASTM C666. In uniaxial tension tests performed on wet cured and frost exposed ECC tensile coupons of the same age, no significant drop in strain capacity was experienced after 300 frost cycles. Both wet cured and freeze thaw specimens exhibited a strain capacity of roughly 3%, which, while lower than the 5% strain capacity mentioned above, fits closely with long term results in specimens of this age which will be discussed below. Recent work on freeze-thaw cycles in the presence of salt concentration reveals strong salt-scaling resistance and durability in ECC [13].

ABRASION AND WEAR TESTING

For roadway surfaces, ECC must provide an adequate surface for driving and braking, while withstanding traffic abrasion. Surface friction and wear track testing was conducted in conjunction with the Michigan Department of Transportation (MDOT) to evaluate the ability of ECC to withstand wheel abrasion and provide sufficient braking friction. A set of four ECC roadway surfaces were cast corresponding to various types of surface texturing. One specimen was tined with a tining rake to produce transverse grooves; another was cured under a textured cloth to simulate wet curing under burlap; a third was textured with Astroturf to roughen the surface, a practice common in Michigan; and a final specimen was topped with coarse sand surface. Due to the presence of fibers, tining to produce grooves or dragging items across the surface proved to be difficult, and resulted in removal of the top layer of fresh material, effectively ruining the finished surface. However, with a number of trials, adequate texturing was achieved.

Specimens were cured for 28 days and subjected to both static friction testing and wear track testing according to Michigan Test Method 111 [14]. Initial friction forces between vehicle tires operating at 65kph and the textured ECC specimens were determined using a static friction tester. All static friction tests were conducted on a wet pavement surfaces. Following initial friction testing, ECC specimens were subjected to 4 million tire passes to simulate long-term pavement wear. After wearing, friction forces were once again determined to assess any deterioration or surface polishing. These final friction forces are defined as the Aggregate Wear

Index (AWI). AWI values for the textured ECC samples tested range from 1.6 to 2.3kN. The established minimum AWI for Michigan trunk line road surfaces is 1.2kN, lower than all ECC surfaces tested, making it a suitable material for roadway surfaces. From this testing, a transverse tined surface treatment, exhibiting an AWI of 2.3kN after 4 million tire passes, is currently recommended for ECC pavement surfaces. Other commonly used concrete pavement texturing methods should also be evaluated in future research to determine improved performance.

5. USING LIFE CYCLE ASSESSMENT TO GUIDE SUSTAINABLE ECC OVERLAY DESIGN

Life cycle assessment (LCA) is an analytical technique for assessing potential environmental burdens, social impacts, and economic costs thereby measuring progress toward sustainability [17]. Together these broad metrics form the triple bottom line of current sustainability indicators. Based on defined framework boundary, LCAs quantify the potential consumption and impacts throughout a product's life cycle from raw material acquisition through production, use, and disposal [18]. An LCA model of a pavement overlay system was developed by Zhang et al. [19] and its application to ECC overlays is presented.

LIFE CYCLE MODEL

The LCA model for pavement overlays divided into six modules: material production, consisting of the acquisition and processing of raw materials; construction, including all construction processes, maintenance activities, and related construction machine usage; distribution, accounting for transport of materials and equipment to and from the construction site; traffic congestion, which models all construction and maintenance related traffic congestion; usage, including overlay roughness effects on vehicular travel and fuel consumption during normal traffic flow; and end of life, which models demolition of the overlay and processing of the materials. Details of each module are described in Zhang et al. [19]. Input and output data from each module are evaluated to capture the material consumption, energy consumption, and environmental impacts of the overlay system throughout its service life. Several datasets are required to provide the life cycle information for input materials or processes. For example, the dataset for ECC production provides the raw material consumption, total primary energy consumption, pollutant emissions, and wastes associated with producing a unit volume of ECC. Raw material consumption quantifies the non-fuel material inputs, such as the mass of cement required. Total primary energy consumption includes the energy required for extraction, refining, transportation, and processing the material. The air and water pollutant emissions and solid wastes are also modeled for each life cycle stage. These datasets and sources can be found in Keoleian and Kendall [20] and Zhang et al. [19].

The LCA model is linked to four external models: (1) a material environmental impact model, SimaPro 7.0 developed by Pre Consultants [21]; (2) a vehicle emissions model, MOBILE 6.2 developed by U.S. Environmental Protection Agency (EPA) [22], and four localized MOBILE 6.2 data inputs for the winter and summer seasons which include annual temperature range, Reid vapor pressure, age distribution of the vehicle fleet, and average vehicle miles traveled data [23]; (3) a construction equipment model, NONROAD, also developed by the EPA [24]; (4) and a traffic flow model developed at the University of Kentucky [25].

GREEN ECC MATERIALS AND PAVEMENTS

As described earlier by Lepech et al. [26], a total of 14 ECC mixes were designed incorporating a variety of industrial waste streams. These wastes include fly ash from coal-fired thermoelectric power generation, a variety of sands and wastes from metal casting processes, post consumer carpet fibers, wasted cement kiln dust from cement production, and expanded polystyrene (EPS) beads from lost foam foundry operations. The mix proportions and material properties of these mix designs are shown in Table 1. The incorporation of industrial wastes is governed by micromechanical models for the design of ECC materials as described in Lepech et al. [2, 27].

A set of metrics capturing consumption and environmental impacts was computed for each of the 14 mix designs. These values result from a life cycle inventory assembled for cement-based materials and summarized by Kendall et al. [18]. These values are shown in Table 2.

6. CONCLUSION

As was found by the co-authors and others, a properly designed ECC overlay system had lower environmental burdens over a 40-year service life as compared to concrete and HMA overlay systems. By extending the service life and minimizing maintenance frequency, the ECC overlay system reduces total life cycle energy by 14%, GHG emissions by 32%, and costs by 40% as compared to conventional overlays. Material, traffic, and pavement roughness effects were identified as the life cycle stages with greatest environmental impacts throughout the overlay system life cycle. Alternative overlay design strategies, such as varying overlay thickness and different maintenance schedules, can be implemented based on local traffic conditions and pavement requirements to achieve even further improvements. Using the presented approach of LCA-guided materials and pavement design, pavement engineers are better able to incorporate high performance pavement materials into applications through quantifiable sustainability indicators and long-proven pavement design methods.

Engineered Cementitious Composites (ECC) exhibit many of the characteristics desirable for high performance pavement applications, including excellent durability, high ductility, and resistance to cracking. As compared to plain concrete, ECC material tests show improved performance in shrinkage cracking behavior, fatigue and substrate bond testing, freeze thaw exposure, abrasion and wear testing, long term material performance, and accelerated weather tests. Furthermore, the use of ECC materials in demonstration projects with the Michigan Department of Transportation, including bridge deck patching and a link slab project, reveal that ECC is a viable high performance material choice for various transportation applications

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