FIELD IMPLEMENTATION AND MONITORING OF BEHAVIOR OF ECONOMICAL AND CRACK-FREE HIGH-PERFORMANCE CONCRETE FOR PAVEMENT AND TRANSPORTATION INFRASTRUCTURE CONSTRUCTIONS – PHASE II

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16. Abstract
Economical and crack-free high-performance concrete (Eco-HPC) is a new class of environmentally friendly and cost-effective high-performance concrete (HPC) that is made of low binder content, high volume of supplementary cementitious materials (SCMs), and shrinkage mitigating materials. The initial phase of research that involved an extensive laboratory investigation indicated that the designed Eco-HPC can secure high resistance to shrinkage cracking, and high strength and durability. The aim of this project was to validate findings of the previous research via field implementation and develop guidelines for the use of Eco-HPC for sustainable transportation infrastructure construction. Two classes of Eco-HPCs were developed for field demonstrations: Eco-Pave-Crete made for pavement construction and Eco-Bridge-Crete for bridge construction. Fresh, mechanical properties, and shrinkage of these Eco-HPC mixtures were validated through laboratory and prototype-scale testing and compared to those obtained using a MoDOT reference mixture. The Eco-Pave-Crete, Eco-Bridge-Crete, and MoDOT reference mixture were proportioned with binder contents of 320 kg/m3 (540 lb/yd3), 350 kg/m3 (590 lb/yd3), and 375 kg/m3 (632 lb/yd3) cementitious materials, respectively. Test results indicate that it is possible to design Eco-HPC with low drying shrinkage ($<$ 300 µstrain after 250 days) and no restrained shrinkage cracking up to 55 days. Prototype-scale slabs cast with Eco-Bridge-Crete exhibited lower shrinkage compared to the reference concrete. Further prototype-scale reinforced concrete beams made with Eco-Bridge-Crete containing more than 50% replacement of cement to SCMs and either 0.35% structural synthetic fibers or recycled steel fibers developed significantly higher flexural strength and toughness. A comprehensive probabilistic life-cycle cost analysis methodology was carried out to quantify the life cycle costs of Eco-HPC and conventional materials that link laboratory-measured parameters to actual field performance. Compared to the MoDOT reference mixture, the optimized Eco-HPC mixtures developed for pavement and bridge applications exhibited approximately 40% lower embodied energy and 55% lower global warming potentials. The use of the proposed Eco-HPC mixtures could lead to reductions of about 4.7% of agency costs and 17.3% of the total life-cycle cost for bridge deck construction and 3.2% of agency cost and 6.2% of the total life-cycle cost for pavement construction in high traffic conditions.

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Asphalt mixtures; Cracking; Field tests; High performance concrete; Infrastructure; Mix design; Pavement performance; Sustainable transportation

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Final Report

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ABSTRACT

Economical and crack-free high-performance concrete (Eco-HPC) is a new class of environmentally friendly and cost-effective high-performance concrete (HPC) that is made of low binder content, high volume of supplementary cementitious materials (SCMs), and shrinkage mitigating materials. The initial phase of research that involved an extensive laboratory investigation indicated that the designed Eco-HPC can secure high resistance to shrinkage cracking, and high strength and durability. The aim of this project was to validate findings of the previous research via field implementation and develop guidelines for the use of Eco-HPC for sustainable transportation infrastructure construction. Two classes of Eco-HPCs were developed for field demonstrations: Eco-Pave-Crete made for pavement construction and Eco-Bridge-Crete for bridge construction. Fresh, mechanical properties, and shrinkage of these Eco-HPC mixtures were validated through laboratory and prototype-scale testing and compared to those obtained using a MoDOT reference mixture. The Eco-Pave-Crete, Eco-Bridge-Crete, and MoDOT reference mixture were proportioned with binder contents of 320 kg/m^3 (540 lb/yd^3), 350 kg/m^3 (590 lb/yd^3), and 375 kg/m^3 (632 lb/yd^3) cementitious materials, respectively. Test results indicate that it is possible to design Eco-HPC with low drying shrinkage ($<$ 300 μstrain after 250 days) and no restrained shrinkage cracking up to 55 days. Prototype-scale slabs cast with Eco-Bridge-Crete exhibited lower shrinkage compared to the reference concrete. Further prototype-scale reinforced concrete beams made with Eco-Bridge-Crete containing more than 50% replacement of cement to SCMs and either 0.35% structural synthetic fibers or recycled steel fibers developed significantly higher flexural strength and toughness. A comprehensive probabilistic life-cycle cost analysis methodology was carried out to quantify the life cycle costs of Eco-HPC and conventional materials that link laboratory-measured parameters to actual field performance. Compared to the MoDOT reference mixture, the optimized Eco-HPC mixtures developed for pavement and bridge applications exhibited approximately 40% lower embodied energy and 55% lower global warming potentials. The use of the proposed Eco-HPC mixtures could lead to reductions of about 4.7% of agency costs and 17.3% of the total life-cycle cost for bridge deck construction and 3.2% of agency cost and 6.2% of the total life-cycle cost for pavement construction in high traffic conditions.

Keywords: Crack-free high-performance concrete; Eco-Bridge-Crete; Eco-Pave-Crete; Instrumentation design and fabrication; Life cycle assessment; Shrinkage; Sustainable materials.

EXECUTIVE SUMMARY

This research project was undertaken to develop a new class of environmentally friendly, cost-effective, and crack-free high-performance concrete (Eco-HPC) for use in pavement (Eco-Pave-Crete) and bridge (Eco-Bridge-Crete) construction. The binder contents of these novel materials were limited to 320 kg/m^3 (540 lb/yd^3) and 350 kg/m^3 (590 lb/yd^3), respectively, and their water-to-cementitious materials ratios (w/cm) were fixed at 0.40 to reduce the paste content, cost, and CO_2 emissions. The Eco-HPCs were optimized to develop high resistance to early-age cracking as well as to secure adequate fresh properties, strength, and durability. A number of parameters affecting concrete performance, including the binder type (slag cement, silica fume, and fly ash) and binder content (320 kg/m^3 [540 lb/yd^3] and 350 kg/m^3 [590 lb/yd^3]), fiber type (synthetic and recycled steel fibers), and shrinkage mitigating materials (expansion agent and lightweight sand) were investigated. The results were compared to those of a MoDOT reference mixture made with a binder content of 375 kg/m^3 (632 lb/yd^3) with 25% of a Class C fly ash (FA25) substitution. Based on the test results, performance-based specifications for Eco-Pave-Crete and Eco-Bridge-Crete were defined. A proposed life-cycle cost analysis (LCCA) approach was employed to link the newly developed construction materials and technologies' laboratory-measurements to field performance data and to those of conventional concrete mixtures used in such applications. The main findings are summarized below.

(1) Performance validation through laboratory standard testing

- The incorporation of fibers (synthetic and recycled steel fibers) in concrete containing a high volume of SCMs was shown to increase the flexural strength by up to 35% compared to the MoDOT reference concrete. The highest flexural strength and toughness values were obtained for the mixture made with 0.35% recycled steel fibers, 20% SL, and 35% FA.

- For a given fiber content, the use of steel fibers recovered from waste tires had two-fold higher flexural toughness compared to the mixture made with synthetic fibers.
- The optimized Eco-HPC mixtures had drying shrinkage of 300 μstrain compared to 450 μstrain for the MoDOT mixture after 250 days. The incorporation of 7.5% Type G EX resulted in early-age expansion of 100 μstrain and shrinkage of 200 μstrain after 250 days of drying.
- Under restrained shrinkage conditions, the MoDOT mixture had an elapsed time to cracking of 24 days. In the case of mixtures made with shrinkage reducing materials, no cracking was observed until 55 days of testing.
- Regardless of the binder type, concrete mixtures made with 7.5% CaO-based EX exhibited an expansion of 20 μstrain compared to the 60 μstrain of shrinkage for the reference mixture under restrained shrinkage.
- All developed Eco-HPCs exhibited frost durability factors varying approximately between 75% and 85% after 300 cycles and scaling mass loss of approximately 700 and 900 g/m^2 (20.6 and 26.5 oz/yd^2) after 50 cycles.

(2) Performance validation through prototype-scale testing

- The control slab made with the MoDOT reference mixture exhibited higher magnitude and rate of shrinkage deformation compared to the optimized Eco-Bridge-Crete mixtures.
- Given expansion induced stresses, the SL20FA35-7.5EX-0.35FRW mixture containing 7.5% CaO-based EX exhibited significant expansion. The magnitude of expansion was shown to vary along the height of slab.

- The incorporation of 25% LWS was shown to be fully effective at reducing shrinkage rate and magnitude. The lowest RH values observed for the FA25, SL20FA35-25LWS, and SL20FA35-7.5EX-0.35FRW mixtures were 82%, 96%, and 90%, respectively.
- Shrinkage deformation values recorded for side and corner points of slabs were larger than those of the sensors located at the center of the slab. This was consistent with results of humidity sensors placed at the side and corner parts of the slab, where larger drop in RH was observed compared to data from the middle sensor.
- The 30-day shrinkage deformation values corresponding to RH sensors were 80 μstrain in shrinkage, 40 μstrain in expansion, and 400 μstrain in expansion for the FA25, SL20FA35-25LWS, and SL20FA35-7.5EX-0.35FRW mixtures, respectively.
- Reinforced concrete beams made with the optimized Eco-HPC containing more than 50% SCM replacement exhibited equivalent or higher ultimate flexural load than of the control beam made with MoDOT reference mixture (FA25).
- For a given beam deflection, the use of 0.35% recycled steel fibers significantly reduced the crack width compared to that of the non-fibrous beams.
- The inclusion of either 0.35% structural synthetic fibers or recycled steel fibers substantially enhanced the toughness of the beam. The SL20FA35-7.5EX-0.35FT, SL60SF5-7.5EX-0.35FRW, and SL20FA35-7.5EX-0.35FRW concrete beams developed 120%, 135%, and 130% higher flexural toughness, respectively, compared to the control beam prepared using MoDOT reference mixture.

(3) Defining performance-based specifications for Eco-Pave-Crete and Eco-Bridge-Crete

The results from the laboratory-testing program and prototype-scale investigation are integrated to define performance-based specifications for the design of Eco-HPC, as summarized in Table 1. The optimized Eco-Pave-Crete and Eco-Bridge-Crete mixtures that meet the required characteristics are presented in Table 2.

Table ES-1 Performance-based specifications for Eco-HPC

Eco-Pave-Crete (with different workability levels)

Property	Value
Binder content	320 kg/m^3 (540 lb/yd^3)
Slump (without fibers)	50 ± 25 mm (2 ± 1 in.)
Slump (with fibers)	100 ± 25 mm (4 ± 1 in.)
Compressive strength at 56 days	≥ 35 MPa (5080 psi)
Drying shrinkage after 120 days (7-d moist curing)	≤ 300 μstrain
Restrained shrinkage cracking potential	Low (time-to-cracking > 28 days according to ASTM C1581)
Frost durability	Adequate (durability factor > 70% after 300 freeze-thaw cycles according to ASTM C666, Proc. A)

Eco-Bridge-Crete (with different workability levels)

Property	Value
Binder content	350 kg/m^3 (590 lb/yd^3)
Slump (without fibers)	100 ± 25 mm (4 ± 1 in.)
Slump (with fibers)	200 ± 25 mm (8 ± 1 in.)
Compressive strength at 56 days	40 to 50 MPa (5800 to 7250 psi)
Drying shrinkage after 120 days (7-d moist curing)	≤ 300 μstrain
Restrained shrinkage cracking potential	Low (time-to-cracking > 28days according to ASTM C1581)
Frost durability	Adequate (durability factor > 70% after 300 freeze-thaw cycles according to ASTM C666, Proc. A)

(4) Life cycle assessment

- The optimum Eco-HPC mixtures for pavement and bridge applications exhibited approximate 40% lower embodied energy and 55% lower global warming potentials (GWP) compared to the MoDOT reference concrete mixtures.
- The developed Eco-HPC can save 4.7% of agency costs and 17.3% of the total life-cycle cost for bridge deck construction and 3.2% of agency cost and 6.2% of the total life-cycle cost for pavement construction in high traffic conditions.

Table ES-2 Candidate Eco-HPC mixtures for field implementation

	Concrete Type Eco-Pave-Crete	Concrete Type Eco-Pave-Crete	Concrete Type Eco-Pave-Crete	Concrete Type Eco-Bridge-Crete	Concrete Type Eco-Bridge-Crete	Concrete Type Eco-Bridge-Crete
Water cement ratio (0.40)	X	X	X	X	X	X
Binder content 320 kg/m3; 540 lb/yd3	X	X	X			
Binder content 350 kg/m3 (590 lb/yd3)				X	X	X
Binder type 75% OPC + 25% Class C FA						
Binder type 60% OPC + 40% Class C FA	X					
Binder type 45% OPC + 20% SL + 35% Class C FA		X	X		X	
Binder type 35% OPC + 60% SL + 5% SF	X			X		
Fiber type and content TUF strand fiber (0.35%)			X			X
Fiber type and content Steel wire from tire (0.35%)						X
Shrinkage-compensating materials 25% lightweight sand	X	X		X	X	
Shrinkage-compensating materials 7.5% Type G expansive agent			X			X

Note: OPC: ordinary portland cement, FA: fly ash, SL: slag cement, and SF: silica fume

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1. INTRODUCTION

1.1. Problem statement

High-performance concrete (HPC) is typically characterized by high binder content, but resulting in higher cost and greater risk of cracking due to thermal, autogenous, and drying shrinkage and eventually reduced service life of the infrastructure. Economical and crack-free high-performance concrete (Eco-HPC) is a new class of environmentally friendly and cost-effective HPC that is developed using low binder content, high volume supplementary cementitious materials (SCMs), and shrinkage mitigating materials (Khayat and Iman, 2014). In the initial phase of the research targeting the development of Eco-HPC that was undertaken with the Missouri Department of Transportation (MoDOT), two classes of Eco-HPC were developed: Eco-Pave-Crete for pavement construction and Eco-Bridge-Crete for bridge deck and transportation infrastructure construction. The binder contents of these mixtures were 320 kg/m^3 (540 lb/yd^3) and 350 kg/m^3 (590 lb/yd^3), respectively. The workability of these mixtures was adjusted to facilitate placement. Both types of Eco-HPCs were optimized to secure low shrinkage and proper strength and durability. Low cracking potential can enhance impermeability and structural properties, leading to prolonged service life.

The research program presented in this report is a follow-up project extended from the initial phase (Khayat and Iman, 2014) aimed at investigating and validating the performance of Eco-HPC mixtures as well as developing guidelines for the use of Eco-HPC for sustainable pavement and transportation infrastructure construction.

1.2. Research objectives

The main objective of this project was to establish guidelines for material selection, mixture design, casting, and performance of such sustainable infrastructure materials through performance validation for field implementation. It is expected that the results obtained from this research work can provide a basis for:

- New mixture design methodology and guidelines for using Eco-HPC for various types of transportation infrastructure and pavement applications;
- Validation of performance improvement when using Eco-HPC in Missouri through substantial information regarding key engineering properties and structural behavior of concrete.

1.3. Research methodology

The research project includes the following tasks:

(1) Pre-qualification of Eco-HPC;

(2) Validation of Eco-HPC performance in prototype-scale elements;

(3) Instrumentation design and fabrication for field implementation;

(4) Life cycle assessment;

(5) Summary and conclusion with main emphasis on mixture proportioning specifications.

Further details of the work tasks are described below.

1.3.1. Task 1 – Pre-qualification of Eco-HPC

The Eco-HPC mixtures optimized through the laboratory investigation from Phase I (Project Number TR2015-03) were further examined. The workability, mechanical properties, and frost durability characteristics of optimized concrete mixtures were further evaluated. The pre-qualified concrete mixtures were then studied for prototype-scale investigation.

1.3.2. Task 2 – Performance validation of Eco-HPC in prototype-scale elements

The task is designed to validate the performance of optimized Eco-HPCs in prototype-scale elements. Focus was placed on shrinkage measurements of slab sections made with optimized Eco-Pave-Crete and flexural performance of reinforced concrete beams cast with the optimized Eco-Bridge-Crete.

1.3.3. Task 3 – Instrumentation design and fabrication for field implementation

Various measuring techniques can be employed to determine residual strain and displacement of the materials used in field implementation. For example, vibrating wire strain gauges (VWSG) and embedded strain gauge can be used for monitoring deformation and temperature variations. The sensors can monitor deformation caused by temperature variations and shrinkage induced deformation in the horizontal and vertical directions in the pavement. Gauges and sensors are placed in mold prior to concrete placement and connected to a data acquisition system. The data logger is connected to a solar panel that charges the data logger battery. The internal relative humidity (RH) of concrete is measured using cast-in sensors to determine the effect of humidity variation on shrinkage deformation.

1.3.4. Task 4 – Life cycle assessment

This task aims to analyze and quantify the environmental impact and degree of sustainability of using Eco-HPC. This includes energy and gas emissions associated with extraction of raw materials, manufacturing process, material transportation, concrete production, and cost. Environmental impact of Eco-Pave-Crete and Eco-Bridge-Crete mixtures that are intended for field implementation is calculated, and the results are compared with those of pavement and bridge structures made with MoDOT reference concrete mixtures.

1.3.5. Task 5 – Development of specifications and recommendations for Eco-HPC

Recommendations for the use of Eco-Pave-Crete for pavement application and Eco-Bridge-Crete for transportation infrastructure construction were developed. These recommendations included information on optimal mixture proportioning and performance-based specifications.

2. PREQUALIFICATION OF MIXTURES THROUGH LABORATORY INVESTIGATION

This section aimed at validating the performance of Eco-HPC mixtures targeted for different construction applications through laboratory standard testing and prototype-scale element evaluations. A number of affecting parameters, including binder type (fly ash [FA], silica fume [SF] and slag cement [SL]) and content (320 kg/m^3 [540 lb/yd^3] and 350 kg/m^3 [590 lb/yd^3]), fiber type (synthetic and recycled steel fibers), and use of shrinkage mitigating materials (expansion agent [EX] and lightweight sand [LWS]), on concrete characteristics were investigated. The results were compared to those of the MoDOT reference mixture. Performance-based specifications for Eco-HPC targeted for different applications were defined.

2.1. Validation of Eco-HPC mixtures targeted for pavement and bridge deck applications

Table 2-1 presents the Eco-Pave-Crete and Eco-Bridge-Crete mixtures that were designed and validated for the purpose of field implementation. The investigated mixtures were prepared with a water-to-cementitious materials ratio (w/cm) of 0.40.

2.1.1. Performance validation through laboratory standard testing

The testing program is summarized in Table 2-2. The unit weight of fresh concrete was 2275 ± 25 kg/m^3 (3835 ± 42 lb/yd^3), and the air content was adjusted at 5% ± 2%. Figure 2.1 compares the mechanical properties of the Eco-Pave-Crete and Eco-Bridge-Crete mixtures to those of the MoDOT reference mixture (375-FA25). The Eco-Bridge-Crete mixtures developed similar compressive strengths as that of the reference mixture. The incorporation of fibers (synthetic and recycled steel fibers) in concrete containing high volume of SCMs developed 35% higher flexural strength than that of the reference mixture. The highest flexural strength and toughness were obtained for the 350-20SL-35FA-7.5EX-0.35FRW mixture made with 0.35% recycled steel fibers (FRW), 20% SL, and 35% FA. For a given fiber content, the use of steel fibers from waste tires had two times higher flexural toughness compared to concrete made with synthetic fibers.

Table 2-1. Candidate Eco-HPC mixtures for field implementation

	Concrete Type: Eco-Pave-Crete	Concrete Type: Eco-Pave-Crete	Concrete Type: Eco-Pave-Crete	Concrete Type: Eco-Bridge-Crete	Concrete Type: Eco-Bridge-Crete	Concrete Type: Eco-Bridge-Crete
Water cement ratio (0.40)	X	X	X	X	X	X
Binder content 320 kg/m3; 540 lb/yd3	X	X	X			
Binder content 350 kg/m3 (590 lb/yd3)				X	X	X
Binder type 75% OPC + 25% Class C FA						
Binder type 60% OPC + 40% Class C FA	X					
Binder type 45% OPC + 20% SL + 35% Class C FA		X	X		X	
Binder type 35% OPC + 60% SL + 5% SF	X			X		
Fiber type and content TUF strand fiber (0.35%)			X			X
Fiber type and content Steel wire from tire (0.35%)						X
Shrinkage-compensating materials 25% lightweight sand	X	X		X	X	
Shrinkage-compensating materials 7.5% Type G expansive agent			X			X

Note: OPC: ordinary portland cement, FA: fly ash, SL: slag cement, SF: silica fume, and TUF: polypropylene / polyethylene synthetic macro-fiber

Table 2-2. Testing matrix for concrete properties

Concrete Property	Concrete Type Eco-Pave-Crete	Concrete Type Eco-Bridge-Crete	Test
Workability	*	*	Unit weight (ASTM C138), air content (ASTM C 231), slump (ASTM C143)
Mechanical properties	*	*	Compressive strength (ASTM C39) at 3, 7, 28, 56, 91 days
Mechanical properties	*	*	Modulus of elasticity (ASTM C469) at 56 days
Mechanical properties	*	*	Splitting tensile strength (ASTM C496) at 56 days
Mechanical properties	*	*	Flexural strength (ASTM C78) at 56, 91 days
Mechanical properties	*	*	Flexural performance of fiber reinforced concrete (ASTM C1609) at 56, 91 days
Shrinkage properties	*	*	Autogenous shrinkage (ASTM C1698) and drying shrinkage (ASTM C157)
Shrinkage properties	*	*	Restrained shrinkage ring test (ASTM C1581)
Durability	*	*	Frost durability (ASTM C 666, A) - selected mixtures
Durability	*	*	De-icing salt scaling (ASTM C 672) - selected mixtures
Durability		*	Surface resistivity (AASHTO T95) at 56 days
Durability		*	Bulk electrical conductivity (ASTM C 1760) at 56 days
Durability	*	*	Abrasion resistance (ASTM C 944) at 56 days

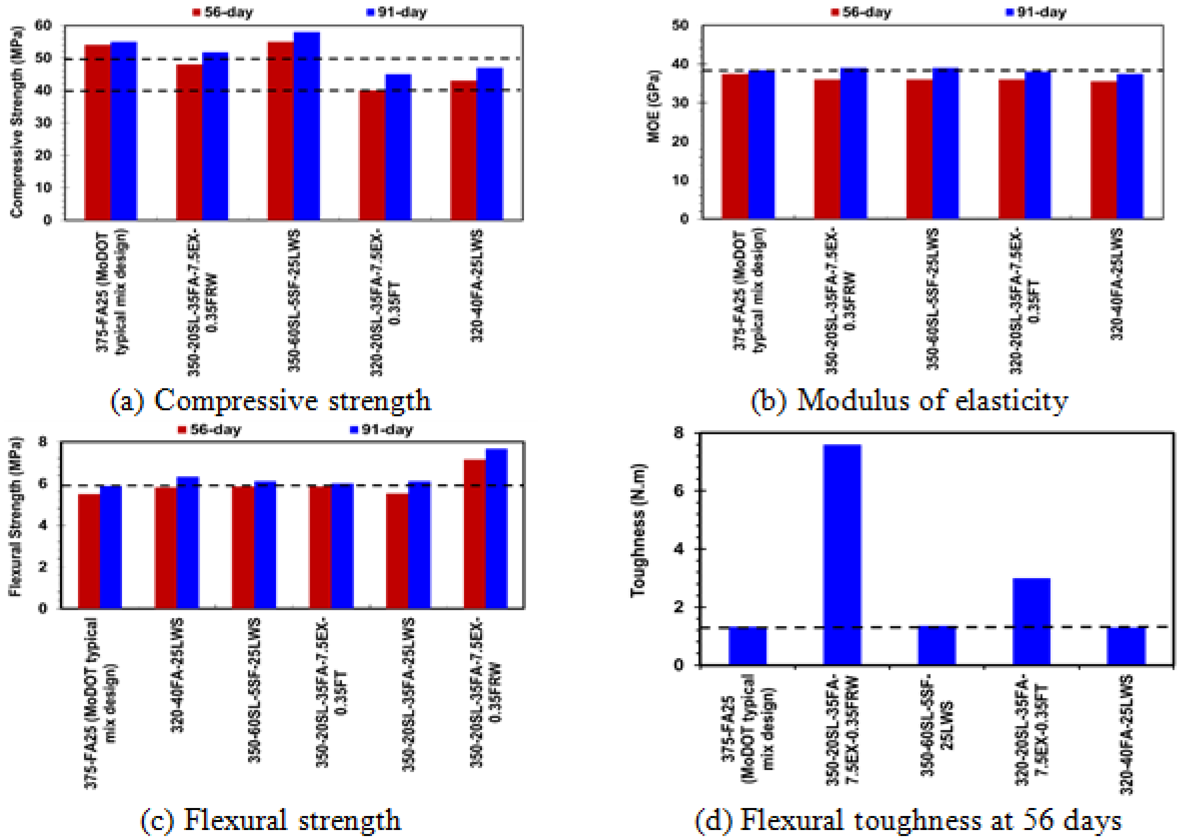
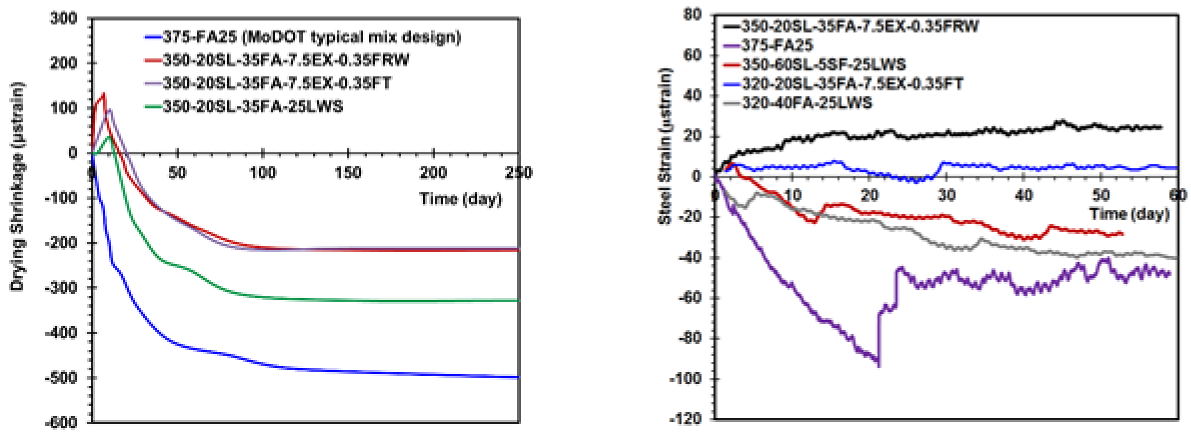


Figure 2.1. Mechanical properties of optimized Eco-HPC mixtures
(Note: 1 N.m = 8.85 lb.in., 1 kN = 0.245 kip)

Figure 2.2 illustrates shrinkage results of optimized Eco-HPC mixtures. The optimized Eco-HPC mixtures had lower drying shrinkage of 300 µstrain after 250 days of drying compared to 450 µstrain for the MoDOT reference mixture. The incorporation of 7.5% CaO-based expansive agent (Type G EX) resulted in a significant early-age expansion of 100 µstrain followed by shrinkage of 200 µstrain after 250 days of drying. The MoDOT mixture exhibited elapsed time to cracking of 24 days under restrained shrinkage conditions. For the mixtures made with shrinkage reducing materials, no cracking was observed after 55 days of testing when the test was stopped. Regardless of binder type, concrete mixtures made with 7.5% Type G EX exhibited an expansion of 20 µstrain compared to 60 µstrain of shrinkage for the reference mixture under restrained shrinkage.



(a) Drying shrinkage (b) Restrained shrinkage

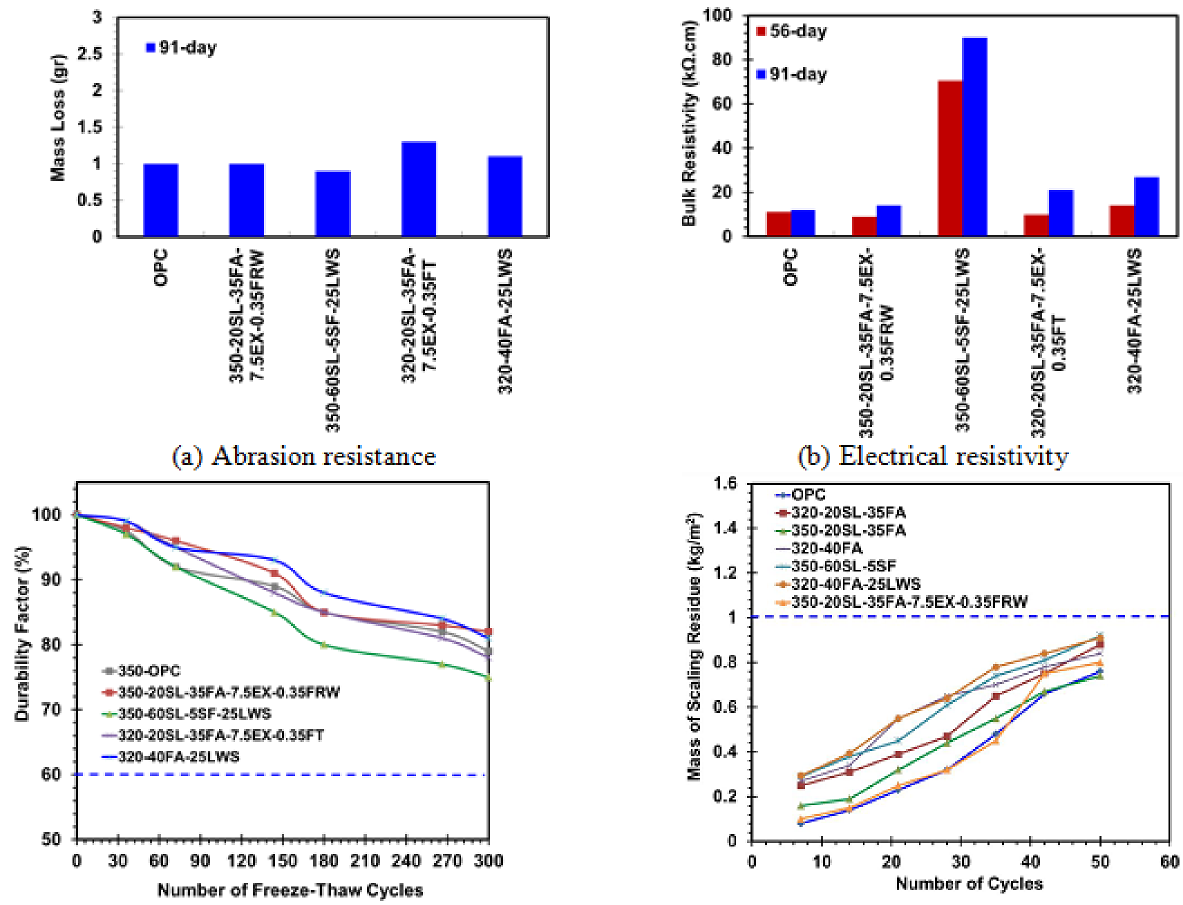
Figure 2.2. Shrinkage evaluation of optimized Eco-HPC mixtures

Durability characteristics, including abrasion resistance, surface resistivity, frost durability factor, and mass of scaling residue of the selected Eco-HPCs are presented in Figure 2.3. All Eco-HPCs developed frost durability factors varying approximately between 75% and 85% after 300 freezing-thawing cycles and scaling mass loss of approximately 700 to 900 g/m^2 (20.6 and 26.5 oz/yd^2) after 50 cycles.

2.1.2. Performance validation through prototype-scale testing

(1) Shrinkage performance validation of Eco-HPC

Table 2-3 shows the three selected concretes. Three slabs measuring 1.8 × 1.8 m (6 × 6 ft) and 150 mm (0.5 ft) in depth were constructed to evaluate variation in RH and shrinkage deformation of the selected Eco-HPC concrete. The high-range water reducer (HRWR) dosage was adjusted to secure a slump consistency of 150 to 200 mm (5.9 and 7.9 in.). The slabs were moist cured for 7 days and were then exposed to air drying in a laboratory environment.



(a) Abrasion resistance (b) Electrical resistivity

(c) Frost durability factor (d) Mass of scaling residue

Figure 2.3. Durability characteristics of optimized Eco-HPC mixtures

The prototype slabs were instrumented by utilizing strain gauges, RH sensors, and thermocouples to monitor the deformation caused by concrete shrinkage, humidity and temperature variations over time. Figure 2.4 illustrates the instrumentation location plan for each slab. Station A, located at the center of the slab, has three embedded strain gauges in the longitudinal direction, three thermocouples, and three RH sensors placed along the height of the slab. Each slab was instrumented at three locations (center, edge, and corner), corresponding to points A, B, and C, respectively, to monitor shrinkage. Stations B and C, located at the edge and corner of the slab, have similar instrumentation layout, including four embedded strain gauges (two in the longitudinal and two in the transverse direction), two thermocouples, and two RH sensors. Sensors were placed at different thicknesses of the slab to monitor strain, temperature, and RH along the height of slabs. Further description of the instrumentation plan is elaborated in Section 3.4.

Table 2-3. Selected Eco-Bridge-Crete mixtures for slab prototype-scale testing

	Concrete Type MoDOT Reference Mixture	**Concrete Type Optimized Eco-Pave-Crete**	**Concrete Type Optimized Eco-Pave-Crete**
Codification	FA25	SL20FA35-25LWS	SL20FA35-7.5EX-0.35FRW
Reinforcement	X	X	X
Water cement ratio (0.40)	X		
Binder content 320 kg/m3; 540 lb/yd3		X	X
Binder content 375 kg/m3 (632 lb/yd3)	X		
Binder type 75% OPC + 25% Class C FA	X		
Binder type 45% OPC + 20% SL + 35% Class C FA		X	X
Fiber type and content Steel fibers from tire (0.35%)			X
Shrinkage-compensating materials 25% LWS		X	
Shrinkage-compensating materials 7.5% Type G EX			X

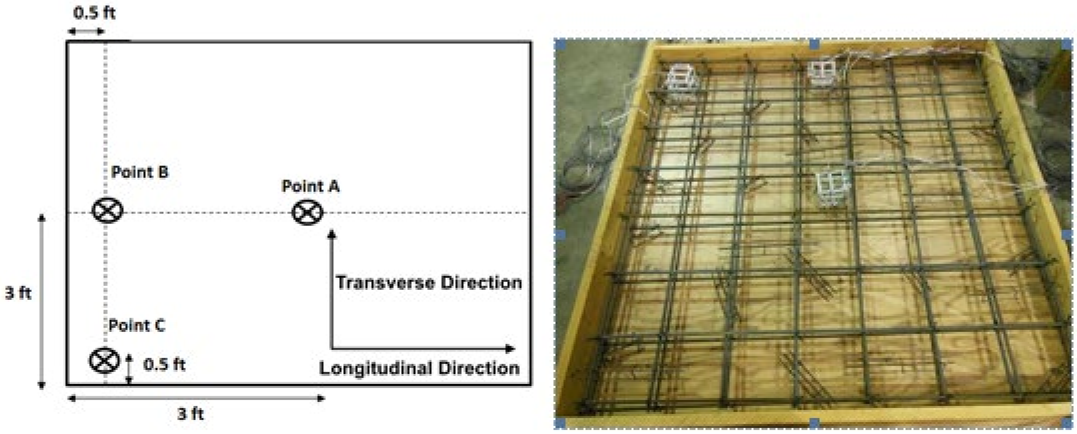


Figure 2.4. Instrumentation location plan for each slab

Figure 2.5 presents the results of shrinkage deformation along the height of the slabs made with the FA25, SL20FA35-25LWS, and SL20FA35-7.5EX-0.35FRW mixtures.

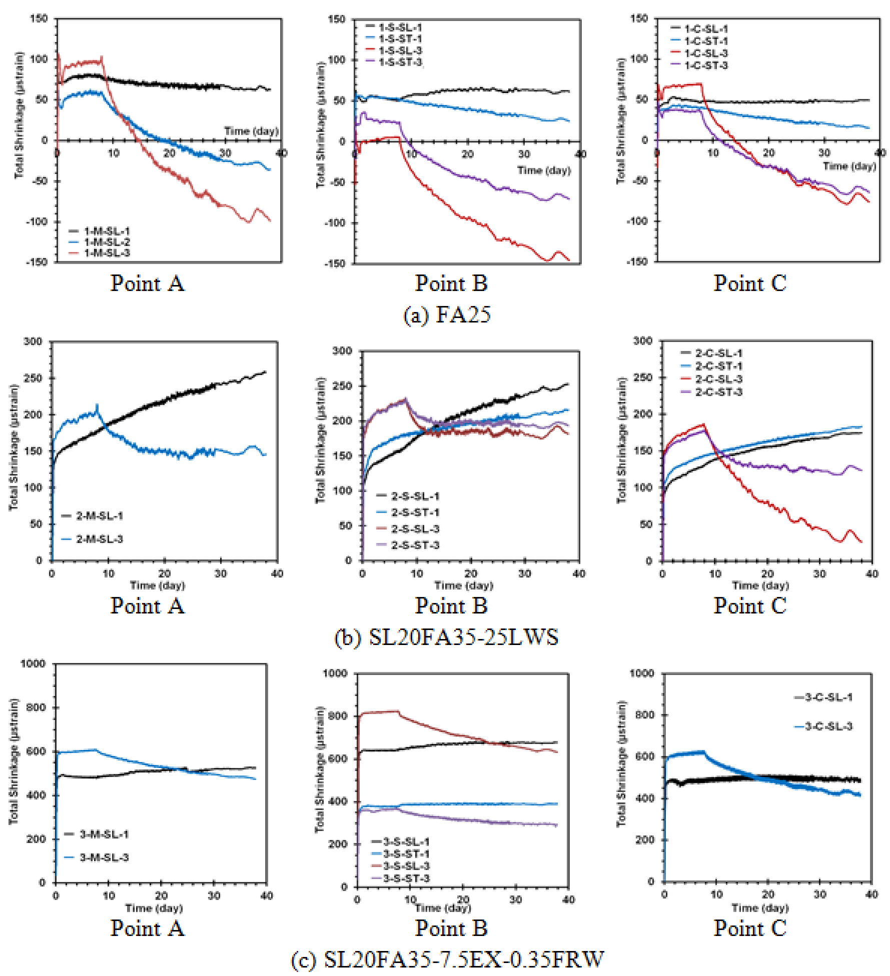


Figure 2.5. Variations of shrinkage over height of three slabs at different locations

The first codification of 1 refers to the slab made with FA25 mixture and M, S, and C refer to measurement points of sensors located at the center, side, and corner points, respectively. The S, H, and T codifications refer to the mean values of strain, humidity, and temperature sensors, respectively. SL and ST denote strain measurements of gauges located in the longitudinal and transverse directions, respectively. Finally, the last number of the 1, 2, and 3 represent values obtained at the bottom, middle, and top parts along the height of concrete slab, respectively.

Shrinkage varied with the concrete mixture and location of the sensors. The slab made with the reference mixture exhibited higher magnitude and rate of shrinkage deformation compared to the two Eco-Bridge-Crete mixtures. Regardless of the concrete composition, the top portions of slabs underwent larger shrinkage compared to the mid-height and bottom parts of the slabs. This is attributed to the faster evaporation rate of the top surface. However, no shrinkage deformation was observed for other locations in the slabs prepared with Eco-Bridge-Crete. Given the expansion induced stresses, the SL20FA35-7.5EX-0.35FRW mixture containing 7.5% CaO-based EX exhibited significant expansion. The magnitude of expansion varied along the height; strain gauges located near the top of slabs had greater expansion compared to values at the middle and bottom parts of the slabs. The incorporation of 25% LWS was fully effective in reducing shrinkage rate and magnitude. No shrinkage was obtained for slabs made with 20% SL and 35% FA binder and 25% LWS. The slab made 25% LWS maintained higher RH after 30 days of drying, which is attributed to the internal curing provided by the LWS.

Figure 2.6 shows the variations in RH along the height of slabs. The shrinkage deformations recorded for side and corner points (stations B and C) of the slab were larger than those of the sensors located at the center of the slab (station A) due to faster rate of evaporation of the concrete near the edge surfaces. Meanwhile, the lowest RH values observed for the FA25, SL20FA35-25LWS, and SL20FA35-7.5EX-0.35FRW mixtures were 82%, 96%, and 90%, respectively. These values were recorded by sensors located at the top corner of the slab. The deformation values corresponding to these sensors was after 30 days and were approximately 80 µstrain of shrinkage, 40 µstrain of expansion, and 400 µstrain of expansion for the FA25, SL20FA35-25LWS, and SL20FA35-7.5EX-0.35FRW mixtures, respectively.

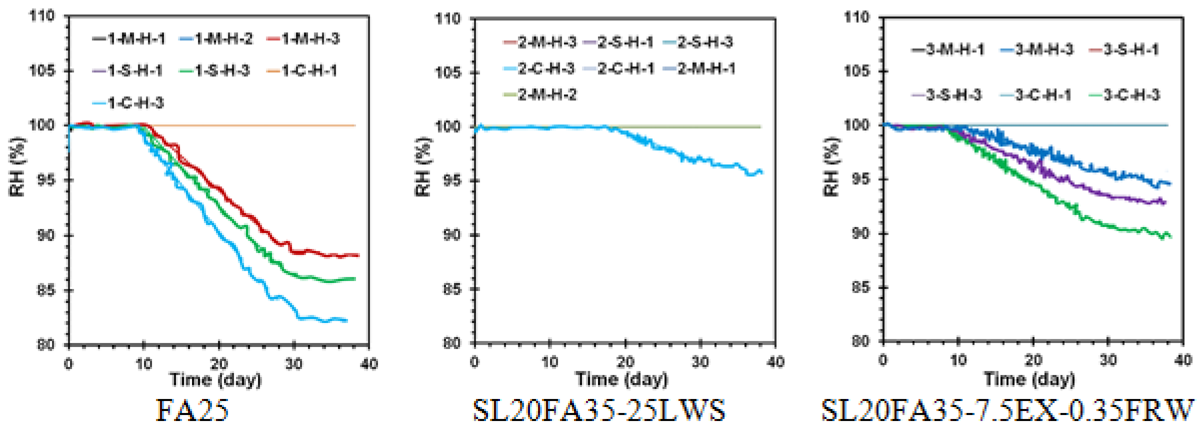


Figure 2.6. Relative humidity variations along height of slabs at different stations

(2) Structural performance validation of Eco-HPC

Flexural properties of reinforced concrete beams made with six Eco-Bridge-Crete mixtures were evaluated and compared to those of the MoDOT reference mixture. Table 2-4 summarizes the concrete mixtures used casting the beams.

The dimensions, reinforcement layout, and position of strain gauges of the tested beams are depicted in Figure 2.7. Each beam measured 2.40 m (94.5 in.) in length with a cross section of 200 × 300 mm (7.9 × 11.8 in.). The beams were designed to be under reinforced (longitudinal reinforcement ratio = 0.72%) and had identical reinforcement layout. The beams were reinforced with three longitudinal #4 bars (4/8 in.) for tension, two longitudinal #3 bars (3/8 in.) for compression, and #3 (3/8 in.) steel stirrups. The side and vertical clear covers of the bars were 25 mm (1 in.). All of the beams had #3 (3/8 in.) stirrups spaced at 10 cm (3.9 in.) within the bearing area to prevent premature failure, as well as #3 (3/8 in.) stirrups spaced at 12.5 cm (4.9 in.) within the middle region.

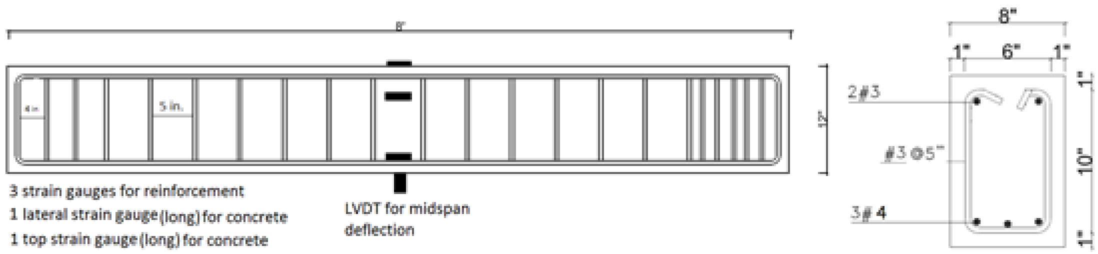


Figure 2.7. Reinforcement layout and location of strain gauge for test beams

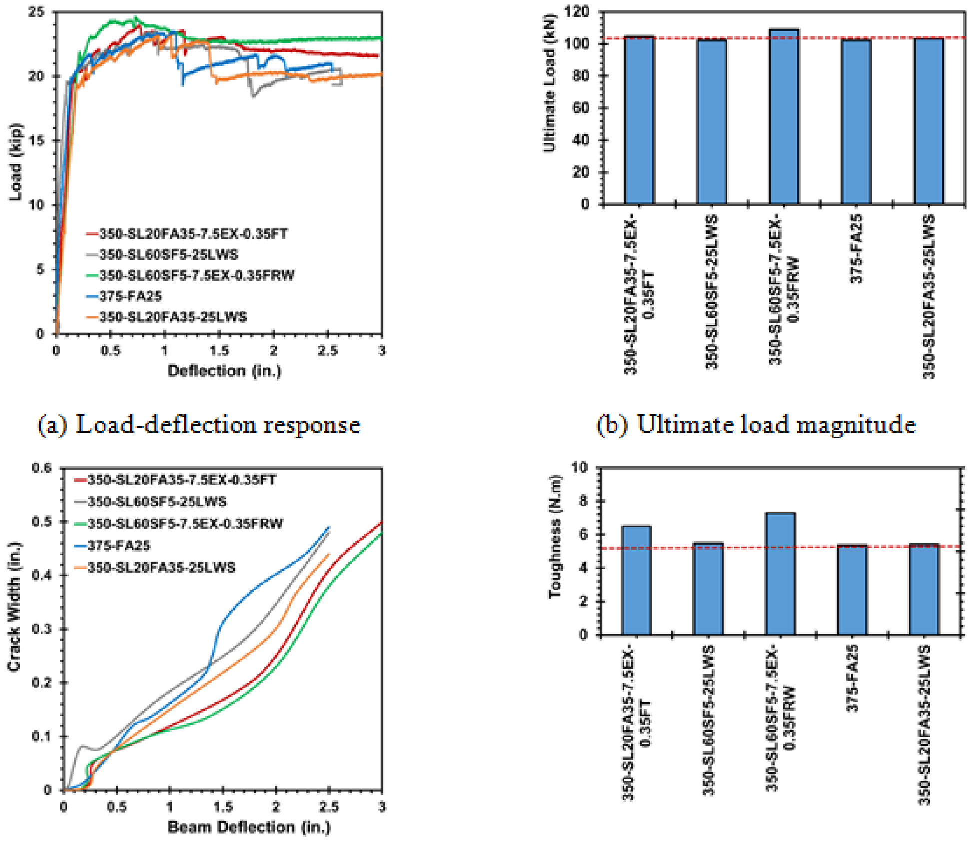
Table 2-4. Selected mixtures to evaluate flexural properties of ECO-HPC

	Concrete Type MoDOT Reference Mixture	Concrete Type Eco-Bridge-Crete	Concrete Type Eco-Bridge-Crete	Concrete Type Eco-Bridge-Crete	Concrete Type Eco-Bridge-Crete	Concrete Type Eco-Bridge-Crete	Concrete Type Eco-Bridge-Crete
Water cement ratio (0.40)	X	X	X	X	X	X	X
Binder content 350 kg/m3 (590 lb/yd3)		X	X	X	X	X	X
Binder content 375 kg/m3 (632 lb/yd3)	X						
Binder type 75% OPC + 25% Class C FA	X						
Binder type 45% OPC + 20% SL + 35% Class C FA		X	X	X	X		
Binder type 35% OPC + 60% SL + 5% SF						X	X
Fiber type and content TUF strand fiber (0.35%)				X			
Fiber type and content Steel fibers from tire (0.35%)					X		X
Shrinkage-compensating materials 25% LWS		X				X	
Shrinkage-compensating materials 7.5% Type G EX				X	X		X

The beams were instrumented using three small strain gauges installed onto the longitudinal reinforcing bars located at the bottom at mid-span; two long strain gauges placed on top and lateral side of concrete surface at the mid-span. A linear variable displacement transducer (LVDT) was used to monitor the vertical deflection of the test beam under flexural testing.

3) Structural performance of Eco-HPC beams

Figure 2.8 compares the structural performance of the Eco-HPC beams. As observed from Figs. 2.6 (a) and (b), the Eco-HPC beams made with relatively high volume SCMs (over 50%) exhibited comparable ultimate load to the MoDOT reference mixture (375-FA25), regardless of the binder composition. The incorporation of either 0.35% structural synthetic fibers or 0.35% recycled steel fibers led to higher ductility and toughness.



(a) Load-deflection response

(b) Ultimate load magnitude

(c) Deflection-crack width relationship

(d) Toughness

Figure 2.8. Structural performance of optimized reinforced Eco-HPC beams (Note: 1 N.m = 8.85 lb.in., 1 kN = 0.245 kip)

The highest load carrying capacity was obtained for the beam made with the 60% SL, 5% SF, and 0.35% recycled steel fiber mixture. The SL20FA35-7.5EX-0.35FT, SL60SF5-7.5EX-0.35FRW, and SL20FA35-7.5EX-0.35FRW concrete beams developed 120%, 135%, and 130% higher flexural toughness, respectively, compared to the reference beam. For a given beam deflection, the use of recycled steel fibers significantly reduced the crack width in relation to that of the non-fibrous beams, as seen from Figure 2.8 (c). The inclusion of LWS improved the post-cracking response and decreased the crack width.

2.2. Defining performance-based specifications for Eco-HPC

Based on the above results, performance-based specifications suitable for the design of Eco-Pave-Crete and Eco-Bridge-Crete mixtures are summarized in Table 2-5. Compared to conventional concrete, the mixture design of Eco-HPC (Eco-Pave-Crete and Eco-Bridge-Crete) requires special attention to material selection and mixture design. The low cement content can be achieved through optimized gradation and packing density of blended aggregates as well as proper selection of binder type and content.

Table 2-5. Performance-based specifications for Eco-Pave-Crete and Eco-Bridge-Crete

Eco-Pave-Crete (with different workability levels)

Property	Value
Binder content	320 kg/m^3 (540 lb/yd^3)
Slump (without fibers)	50 ± 25 mm (2 ± 1 in.)
Slump (with fibers)	100 ± 25 mm (4 ± 1 in.)
Compressive strength at 56 days	≥ 35 MPa (5080 psi)
Drying shrinkage after 120 days (7-d moist curing)	≤ 300 μstrain
Restrained shrinkage cracking potential	Low (time-to-cracking > 28 days according to ASTM C1581)
Frost durability	Adequate (durability factor > 70% after 300 freeze-thaw cycles according to ASTM C666, Proc. A)

Eco-Bridge-Crete (with different workability levels)

Property	Value
Binder content	350 kg/m^3 (590 lb/yd^3)
Slump (without fibers)	100 ± 25 mm (4 ± 1 in.)
Slump (with fibers)	200 ± 25 mm (8 ± 1 in.)
Compressive strength at 56 days	40 to 50 MPa (5800 to 7250 psi)
Drying shrinkage after 120 days (7-d moist curing)	≤ 300 μstrain
Restrained shrinkage cracking potential	Low (time-to-cracking > 28days according to ASTM C1581)
Frost durability	Adequate (durability factor > 70% after 300 freeze-thaw cycles according to ASTM C666, Proc. A)

3. INSTRUMENTATION DESIGN AND FABRICATION FOR FIELD IMPLEMENTATION

The details of sensors and data acquisition systems required for field implementation were finalized with the collaboration of MoDOT. Two data acquisition systems were prepared to monitor deformation, temperature, and RH in concrete elements. Table 3-1 summarizes the list of instrumentation used for the data acquisition system.

Table 3-1. Equipment required for instrumentation

Item	Number
Data acquisition system	2
Solar panel	2
Concrete strain gage	72
Relative humidity sensor	36
Thermocouple	4 roll
Wire	16 roll
Modem	2

3.1. Embedded strain gauge

Embedment strain gauges (KM-120-120-H2-11, manufactured by KYOWA) were selected to monitor shrinkage of concrete, as shown in Figure 3.1. The sensor has an outer body of 120 mm (4.7 in.) sensing grid with an effective gauge length of 75 mm (3.0 in.). The gauge is waterproof and is designed to be placed in fresh concrete to measure shrinkage deformation of the concrete.

Figure 3.1. Embedded strain gauge for monitoring shrinkage deformation

3.2. Thermocouple

The thermocouple wire (UX-08542-24, manufactured by Coleparmer) is a Type T 20 gauge wire. This thermocouple consists of copper and constantan wires that are functional between -250 to 250° C (-418 to 482 °F). The ends of the solid thermocouple wires are twisted and soldered to ensure adequate electrical connection, as shown in Figure 3.2.

Figure 3.2. Thermocouple used for concrete temperature measurement

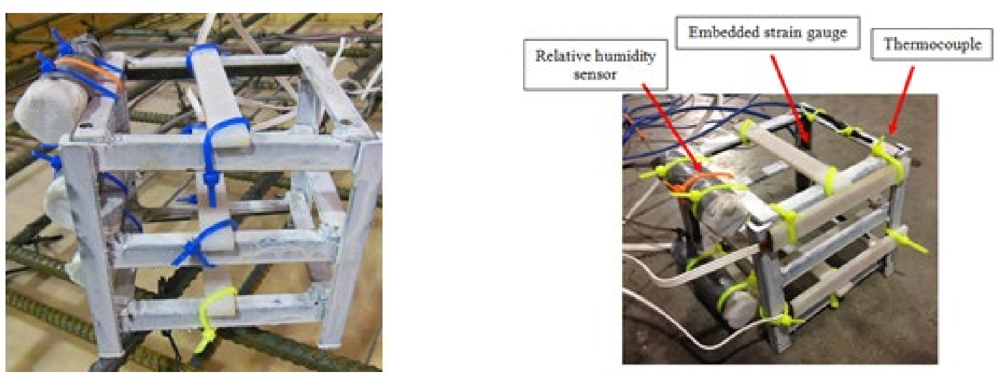
3.3. Relative humidity sensor

The small (6 × 20 mm [0.24 × 0.79 in.]) capacitive RH sensors (HIH-4030, manufactured by Sparkfun) are used to measure the RH inside the concrete. The accuracy of the sensors reported by the manufacturer is ± 2% RH at RH values of 10% to 90% RH; this can be on the order of ± 4% at 100% RH. In order to embed the RH sensor in concrete, the RH sensor is placed inside a PVC tube, and the end of the tube is covered by Gore-Tex to allow moisture transmission, while preventing the penetration of liquid water and solid particles, which could lead to error in measurements. Figure 3.3 shows the encapsulated RH sensor before it is embedded in concrete.

Figure 3.3. Encapsulated relative humidity sensor before embedment in concrete

3.4. Instrumentation layout

Figure 3.4 shows the proposed instrumentation layout, including embedded concrete strain gauges, RH sensors, and thermocouples for the structural health monitoring of Eco-HPC. Sensors can be placed at different locations/heights to monitor the concrete shrinkage at various depths along the thickness of concrete sections (bridge decks and pavements).



(a) (b)

Figure 3.4. Instrumentation layouts for (a) Layout A: 3 embedded strain gauges in longitudinal direction, 3 thermocouples and 3 RH sensors and (b) Layout B: 4 embedded strain gauges (2 longitudinal and 2 transverse directions), 2 thermocouples and 2 RH sensors

Both strain data and the temperature data can be recorded using a Campbell Scientific Data acquisition system. Lead wires from the strain gages are routed through either an AM416 or an AM16-32 multiplexer, using a separate completion module for each gage on the multiplexer, or using a single completion module for all the gages positioned between the multiplexer and the datalogger, as shown in Figure 3.5. The system is powered by a 12 V battery for which the charge is maintained using a solar panel.

Figure 3.5. Data acquisition system for data collection

Slabs and reinforced concrete flexural elements can be instrumented using strain gauges, RH sensors, and thermocouples similar to the systems elaborated in Section 2.1.2 to monitor the deformation caused by concrete shrinkage, humidity and temperature variations over time. A similar configuration of sensors shown in Figure 2.4 can be used in pavement or bridge deck sections to monitor in-situ properties at the various locations along the section and height of concrete elements.

Flexural beam elements can be instrumented using similar strain gauges to monitor deformation in the longitudinal reinforcing bars, stirrups, and concrete, as in the prototype beams elaborated in Figure 2.7.

4. LIFE CYCLE COST ASSESSMENT

Life cycle cost analysis (LCCA) is an effective tool that can provide decision-makers with important information in assessing inputs and outputs. LCCA was carried for the Eco-Pave-Crete and Eco-Bridge-Crete and the conventional MoDOT reference mixture. This chapter presents a summary of the LCCA that was carried out in collaboration with Dr. Kaan Ozbay and his team at New York University Polytechnic Institute as a collaborative effort of the conjunction with RE-CAST University Transportation Center. Project-level LCCA is performed by summing up the monetary equivalent of all benefits and costs at their respective time of occurrence and are converted into a common time dimension so that different alternatives can be compared correctly. A general expected life-cycle cost up to time, T, of known conventional material, LCC(T), can be expressed as below:

$$\mathrm{LCC(T) = CC + CM(T) + CR(T) + CU(T) + CS(T) + SV} \qquad \text{(Eq. 1)}$$

where LCC is the Life-Cycle Cost (dollars), CC is the Construction Cost (dollars), CM is the Maintenance and repair Cost (dollars), CR is the Rehabilitation Cost (dollars), CU is the User Cost (dollars), CS is the Socio-economic Cost (dollars), SV is the Salvage Value (dollars), T is the Time (year). Generally, the rate of deterioration is expected to gradually increase with time. In this example, only the differential user and societal costs that are expected to occur during work zone periods are computed. Note that although including user costs is noted as a best-practice by the FHWA, it could greatly dominate total life-cycle costs, especially in the case of urban projects. It is suggested by the Illinois Department of Transportation (IDOT) (Holland 2012) to use a weighted factor (0.3 in this example) for the user cost when calculating the total life cycle cost. In this example, agency costs include initial construction, maintenance, and rehabilitation costs as well as the salvage value. For the bridge deck, the rehabilitation cost can be broken down into four categories (NJDOT 2015): a) the cost of replacing the structure (include demolition and traffic control), b) approach roadway work, c) traffic staging and d) preliminary engineering. Rehabilitation cost is assumed to be 1.8 times the new bridge initial construction cost. Maintenance cost is assumed to be 5% of the initial construction cost. For pavement, miscellaneous mobilization, and preliminary engineering costs are assumed to be 20%, 5%, 9.5% for initial construction and 9.5%, 1.9%, 9.5% for rehabilitation (Missouri Department of Transportation 2004), respectively. Maintenance costs for both pavement alternatives are assumed to be the same over the entire design lives so they are not inputted into the LCCA for the pavement example. Salvage value is the value of an investment alternative at the end of the analysis period. This is usually included as a benefit or negative cost in agency cost. The full report is attached in the APPENDIX.

In the LCCA, an approach based on hypothesized improvement rate was proposed to compare the expected improvement rate of Eco-HPC. The proposed approach attempted to link the new construction materials laboratory-measured data with actual field performance data to overcome the challenges of limited data. A web-based user-friendly LCCA software tool developed to make use of the existing network-wide data and deterioration models was employed in this analysis and is briefly discussed herein. The traffic data is obtained from one of the I-80 highway section in New Jersey, 0.7 miles east of Passaic River, for demonstration purposes only. This bridge has relatively heavy traffic as is often used for LCCA.

4.1. Embodied energy and global warming potentials of different mixtures

The National Ready Mix Concrete Association (NRMCA) sustainable concrete carbon calculator was employed to determine the embodied total energy and CO_2 emission associated with material manufacturing process, material transportation, and concrete production. Figure 4.1

compares the variation in embodied energy, or primary energy consumption (PEC) and global warming potentials (GWP) with the mixture proportioning. The optimum Eco-PCC mixtures developed for pavement (Alt B2) and bridge (Alt A2) applications exhibited approximately 40% lower embodied energy and 55% lower GWP compared to the MoDOT reference concrete mixtures.

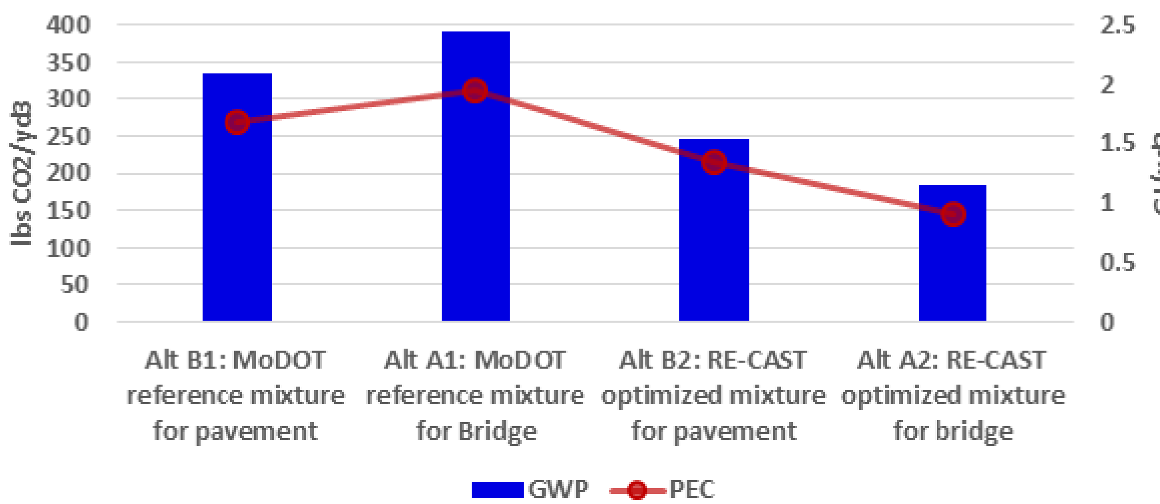


Figure 4.1. Variation in PEC and GWP of different mixtures (Mehdipour 2016)

4.2. Final deterministic LCCA results

A deterministic approach was employed to calculate the environmental impact of the Eco-HPC and MoDOT reference concrete mixtures used for field implementation. Estimated values or models based on historical data were used as inputs to quantify costs in this method. The agency costs include initial construction, maintenance, and rehabilitation costs, as well as the salvage value.

For a concrete bridge deck, the rehabilitation (i.e., replacement of deteriorated section) cost includes four categories: (a) the cost of replacing the structure, including demolition and traffic control, (b) approach roadway work, (c) traffic staging, and (d) preliminary engineering (NJDOT 2015). Rehabilitation cost is assumed to be 1.8 times of the new bridge initial construction cost. Maintenance cost is assumed to be 5% of the initial construction cost. For concrete pavement, the rehabilitation cost includes slab replacement, treatment-diamond grinding, miscellaneous and mobilization, as well as preliminary engineering (MoDOT 2004). Maintenance costs for both alternatives are assumed to be the same over the entire design lives so they are not inputted into the LCCA for the pavement example. Salvage value is the value of an investment alternative at the end of the analysis period. This is usually included as a benefit or negative cost in agency cost.

The final deterministic LCCA results are summarized in Table 4-1. The application of the proposed Eco-Bridge concrete is shown to save 4.7% of agency costs and 17.3% of the total life-cycle cost for the bridge deck. Similarly, savings of 3.2% of agency cost and 6.2% of the total life-cycle cost can be obtained with Eco-Pave concrete. If only agency costs are evaluated, alternatives can be considered similar or equivalent because the difference between agency costs of alternatives is less than 10%. However, the benefit in user costs especially in the case of the bridge deck rehabilitation/replacement and potential energy consumption and GWP savings play an important role and should not be ignored. Higher rehabilitation costs associated with the convetional concretes are due to the shorter life period per year as compared to the proposed Eco-HPC mixtures

Table 4-1. LCCA example work flow – deterministic outputs

I. Agency cost ($)	Alt A1: Conventional Concrete Bridge	Alt A2: Eco-Bridge-Crete
Initial construction cost ($):	3,108,020	3,484,505
Maintenance cost ($):	852,457	955,718
Rehabilitation cost: (A) Replace the structure ($):	1,083,799	779,915
Rehabilitation cost: (B) Approach roadway work ($):	68,520	38,996
Rehabilitation cost: C) Traffic staging ($):	287,783	163,782
Rehabilitation cost: (D) Preliminary engineering ($):	143,892	81,891
Total rehabilitation cost (s):	1,479,385	1,064,585
Salvage value ($):	-203,162	-512,487
Total agency cost ($):	$5,236,700	$4,992,321

I. Agency cost ($)	Alt B1: Conventional concrete pavement	Alt B2: Eco-Pave-Crete
Initial construction cost ($):	322,748	355,396
Maintenance cost ($):	Maintenance cost is assumed to be the same for both alternatives and is neglected in this study	Maintenance cost is assumed to be the same for both alternatives and is neglected in this study
Rehabilitation cost: (A) Slab replacement (1.5%) ($):	7,430	5,958
Rehabilitation cost: (B) Treatment -diamond grinding ($)	6,896	5,444
Rehabilitation cost: (C) Miscellaneous & mobilization ($)	2,067	1,645
Rehabilitation cost: (D) Preliminary engineering($)	1,723	1,371
Total rehabilitation cost (s):	18,116	14,419
Salvage value ($):	0	-39,871
Total agency cost ($):	$340,864	$329,945

II. User cost ($)	Alt A1: Conventional Concrete Bridge	Alt A2: Eco-Bridge-Crete
Traffic delay cost ($):	$25,732,076	$19,216,750
Vehicle operation cost ($):	$1,727,985	$1,280,384
Crash risk cost ($):	$25,153	$15,659
Total user cost ($):	$25,161,738	$20,512,793

II. User cost ($)	**Alt B1: Conventional concrete pavement**	**Alt B2: Eco-Pave-Crete**
Traffic delay cost ($):	$1,387,082	$1,281,998
Vehicle operation cost ($):	$117,318	$100,305
Crash risk cost ($):	$10,279	$7,600
Total user cost ($):	$1,514,679	$1,389,903

III. Social cost ($)	**Alt A1: Conventional Concrete Bridge**	**Alt A2: Eco-Bridge-Crete**
Air pollution cost ($):	$7,307	$4,549
Total social cost ($):	$7,307	$4,549

III. Social cost ($)	**Alt B1: Conventional concrete pavement**	**Alt B2: Eco-Pave-Crete**
Air pollution cost ($):	$2,986	$2208
Total social cost ($):	$2,986	$2,208

IV. Life cycle cost	**Alt A1: Conventional Concrete Bridge**	**Alt A2: Eco-Bridge-Crete**
Total life cycle cost:	$13,489,571	$11,256,927
Benefit:		**Total life cycle cost: -17.34%** **Agency cost: -4.67%, user cost: -25.37%, social cost: -37.74%** (user cost factor: 0.3, social cost factor: 1.0)

IV. Life cycle cost	**Alt B1: Conventional concrete pavement**	**Alt B2: Eco-Pave-Crete**
Total life cycle cost:	$798,254	$749,123
Benefit:		**Total life cycle cost: -6.15%** **Agency cost: -3.20%, user cost: -8.24%, social cost: -26.06%** (user cost factor: 0.3, social cost factor: 1.0)

5. SUMMARY AND CONCLUSIONS

This research project was undertaken to establish guidelines for material selection, mixture design, and performance of Eco-HPC that can be applied for transportation infrastructure applications. Two classes of Eco-HPCs were developed: Eco-Pave-Crete for pavement construction and Eco-Bridge-Crete for transportation infrastructure construction. The binder contents of these novel materials were limited to 320 kg/m^3 (540 lb/yd^3) and 350 kg/m^3 (590 lb/yd^3), respectively, and their w/cm was fixed at 0.40. Fresh, mechanical properties, and shrinkage were validated through laboratory standard testing. To validate shrinkage behavior, three prototype-scale concrete slabs made of three optimized concrete mixtures were constructed and compared to the MoDOT reference mixture. In addition, seven reinforced concrete beams, including a beam made with the MoDOT reference mixture, were cast to evaluate the flexural properties of optimized Eco-Bridge-Crete mixtures. LCCA was conducted to compare the environmental impact between the Eco-HPC and MoDOT reference mixtures. The main findings are summarized below.

5.1. Performance validation through laboratory standard testing

- The incorporation of fibers (synthetic and recycled steel fibers) in concrete containing a high volume of SCMs was shown to increase the flexural strength by up to 35% compared to the MoDOT reference concrete. The highest flexural strength and toughness values were obtained for the mixture made with 0.35% recycled steel fibers, 20% SL, and 35% FA.
- For a given fiber content, the use of steel fibers recovered from waste tires had two-fold higher flexural toughness compared to the mixture made with synthetic fibers.
- The optimized Eco-HPC mixtures had drying shrinkage of 300 μstrain compared to 450 μstrain for the MoDOT mixture after 250 days. The incorporation of 7.5% Type G EX

resulted in early-age expansion of 100 μstrain and shrinkage of 200 μstrain after 250 days of drying.

- Under restrained shrinkage conditions, the MoDOT mixture had an elapsed time to cracking of 24 days. In the case of mixtures made with shrinkage reducing materials, no cracking was observed even after 55 days of testing.
- Regardless of the binder type, concrete mixtures made with 7.5% CaO-based EX exhibited an expansion of 20 μstrain compared to the 60 μstrain of shrinkage for the reference mixture under restrained shrinkage.
- All developed Eco-HPCs exhibited frost durability factor varying approximately between 75% and 85% after 300 cycles and scaling mass loss of approximately 700 and 900 g/m^2 (20.6 and 26.5 oz/yd^2) after 50 cycles.

5.2. Performance validation through prototype-scale testing

- The control slab made with the MoDOT reference mixture exhibited higher magnitude and rate of shrinkage deformation compared to the optimized Eco-Bridge-Crete mixtures.
- Given expansion induced stresses, the SL20FA35-7.5EX-0.35FRW mixture containing 7.5% CaO-based EX exhibited significant expansion. The magnitude of expansion was shown to vary along the height of the slab.
- The incorporation of 25% LWS was shown to be fully effective at reducing shrinkage rate and magnitude. The lowest RH values observed for the FA25, SL20FA35-25LWS, and SL20FA35-7.5EX-0.35FRW mixtures were 82%, 96%, and 90%, respectively.
- Shrinkage deformation values recorded for side and corner points of slabs were larger than those of the sensors located at the center of the slab. This was consistent with results of

humidity sensors placed at the side and corner parts of slab, where larger drop in RH was observed compared to data from the middle sensor.

- The 30-day shrinkage deformation values corresponding to RH sensors were 80 μstrain in shrinkage, 40 μstrain in expansion, and 400 μstrain in expansion for the FA25, SL20FA35-25LWS, and SL20FA35-7.5EX-0.35FRW mixtures, respectively.
- Reinforced concrete beams made with the optimized Eco-HPC containing more than 50% SCM replacement exhibited equivalent or higher ultimate flexural load than of the control beam made with MoDOT reference mixture (FA25).
- For a given beam deflection, the use of 0.35% recycled steel fibers significantly reduced the crack width compared to that of the non-fibrous beams.
- The inclusion of either 0.35% structural synthetic fibers or recycled steel fibers substantially enhanced the toughness of beam. The SL20FA35-7.5EX-0.35FT, SL60SF5-7.5EX-0.35FRW, and SL20FA35-7.5EX-0.35FRW concrete beams developed 120%, 135%, and 130% higher flexural toughness, respectively, compared to the control beam prepared using MoDOT reference mixture.

5.3. Life cycle assessment

- The optimum Eco-HPC mixtures exhibited approximate 40% lower embodied energy and 55% lower global warming potential (GWP) compared to the MoDOT reference concrete mixtures.
- The developed Eco-HPC can save 4.7% of agency costs and 17.3% of the total life-cycle cost for bridge deck construction and 3.2% of agency cost and 6.2% of the total life-cycle cost for pavement construction in high traffic conditions.

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APPENDIX - LIFE CYCLE ASSESSMENT

A.1 Introduction

Thousands of existing structures in the U.S. are in need of condition assessment and renovation. In the 2013 Report Card for American's Infrastructure published by the American Society of Civil Engineering (ASCE), majority of the groups of infrastructure systems (bridges, rail, roads, etc.) fell below a C grade (Herrmann 2013). An estimated investment of 3.6 trillion dollars is estimated to be needed by 2020 to bring the nation's infrastructure to a grade of C or better based on the same report. Aging facilities, growing technical and environmental requirements of the transportation infrastructure, and increasing costs associated with maintenance and repair has led agencies to seek development of innovative materials for construction and maintenance, as well as reliable decision-making tools for cost-effective transportation management and investments.

The sustainability of our urban transportation infrastructure depends on the adoption of new construction materials and technologies with great promise for improved performance and productivity. However, most of the agencies would like to know life cycle costs of these new construction materials and technologies before they can replace the traditional ones. Life cycle cost analysis (LCCA) is an effective tool that can assist decision-makers in the development of optimum investment strategies by accurately assessing internal and external costs of transportation projects while satisfying agency budget constraints. The RE-CAST research team aims to provide multi-scale and multi-disciplinary studies to fast-track the acceptance of the new generation of cement-based materials to achieve a more sustainable transportation infrastructure. Such new generation innovative materials will have several advantages over conventional materials such as more cost-effective and longer service life, more efficient use of resources in construction operations, and minimizing construction duration and traffic delays using certain construction methodologies. But it remains a challenge to reliably estimate their costs and life time performance due to very limited "field implementation" data. In light of all these complications, this section presents the research effort of conducting life cycle cost analysis for both conventional and new-technology materials to support decision making, considering agency, user, as well as society costs. The proposed approach will specifically try to link the new construction materials and technologies' laboratory-measured data with actual field performance data to overcome the challenges of limited data.

Two different approaches are proposed: 1) Apply a hypothesized improvement rate to the deterioration functions of existing and well-known materials to represent the expected improved performance of a new material compared with a conventional material with relatively similar characteristics; 2) Utilize a correlation function between the results of laboratory tests and field performance of known materials to predict the expected performance of a new material based only on the data from its laboratory tests. Both methods are treated probabilistically to be able to deal with the high level of uncertainty due to the length of analysis period, as well as the lack of real-world performance data, especially in the case of novel materials. In addition, a web-based user-friendly LCCA software tool developed to make use of the existing network-wide data and deterioration models is also briefly discussed. This new software tool will allow prospective users to perform this novel LCCA methodology for more effective decision making and resource allocation. This section is concluded with a LCCA example for one of the new materials developed in this project, which was conducted by New York University.

A.2 Literature review

In 1998, an interim Federal Highway Administration (FHWA) technical bulletin (FHWA 1998), "Life-Cycle Cost Analysis in Pavement Design," was developed under FHWA Demonstration Project 115. This report recommends step-by-step procedures for conducting life cycle cost analysis at the project level and has become the agency's guidance document for LCCA. It is still one of the most referenced documents in the LCCA literature. One of its most important contributions was the user cost calculations and the introduction of reliability concepts for LCCA via the use of Monte Carlo simulation. In August 2002, FHWA published another important document, "Life-Cycle Cost Analysis Primer" (FHWA 2002) followed by the development of RealCost software (FHWA 2004). Both of them are intended to provide sufficient background and training for transportation officials to properly use LCCA for evaluating transportation project alternatives.

FHWA and State Highway Agencies (SHAs) recommend LCCA as an important technique for supporting transportation investment decisions. LCCA can be used to evaluate design, maintenance, and preservation strategies for all types of assets, such as pavement or bridges. Guided by FHWA, SHAs along with MAP-21 (USDOT 2012), many state departments of transportation (DOTs) incorporated life cycle cost consideration in their decision-making process and transportation asset management.

A.1 shows a brief summary from seven states in terms of the analysis period used for pavement or bridges, discount rate, evaluation methods, consideration of probabilistic approach and user cost (VDOT 2011, Caltrans 2013, Ozbay et al. 2002, FDOT 2013, Luhr 2015, ODOT 2014, CDOT 2015).

Table A.1 Summary of seven state DOTs LCCA practices

State DOT	Analysis period (years)	Discount rate	Evaluation methods	Probabilistic approach	User cost
VDOT	Pavement: 50	4%	PV/EUAC	No	No
CalTrans	Pavement: 20, 35, 55	4%	PV/EUAC	No	Yes
NJDOT	Pavement: 35-40	Probability distribution	NPV/EUAC/B/C/IRR	No	Yes
NJDOT	Bridges: >=75	Probability distribution	NPV/EUAC/B/C/IRR	Yes	Optional
FDOT	Pavement: 40	3.5%	PV	No	Yes
WSDOT	Pavement: 50	4%	NPV/EUAC	No	No
ODOT	Pavement: 35	OMB discount rate	PV	No	Yes
CDOT	Pavement: 40	2.6%	PV	No	Yes

Note: PV = Present Value, EUAC = Equivalent Uniform Annual Costs, NPV = Net Present Value, B/C = Benefit/Cost, IRR = Internal Rate of Return

Numerous studies have applied LCCA to roads and bridge structures in terms of maintenance and replacement strategies or management tools in the last two decades, however, not much work has been conducted dealing with new construction material/technology and conventional materials/technology. Table A.2 lists six studies involving new technology or materials (Ehlen 1997, Horvath 2004, Keoleian et al. 2005, Cusson, Lounis, and Daigle 2010, Eamon et al. 2012, Soliman and Frangopol 2014). Clearly, there are not many studies that have applied probabilistic approach to deal with the high uncertainty that new materials or construction technologies carry.

Table A.2 Literature review on new construction materials and technologies

Study	New material/ design	Applications	Agency cost	User cost	Social cost	Probabilistic	New material future performance
Ehlen, 1997	Fiber-reinforced polymer composites	Bridge deck	Yes	Yes	No	No	State DOT Estimates and Research Model
Horvath, 2004	Recycled materials	Pavement	Yes	Yes	Yes	No	Model
Keoleian et al., 2005	Engineered cementitious composite	Bridge link slab	Yes	Yes	Yes	No	State DOT Estimates
Cusson et al., 2010	High-performance concrete	Bridge deck	Yes	No	No	No	Model
Eamon et al., 2012	Carbon fiber reinforced polymer	Bridge superstructure	Yes	Yes	No	Yes	State DOT practices
Soliman and Frangopol 2014	Corrosion-resistant steel	Steel bridge	Yes	Yes	Yes	Yes	Assumption

In addition, various LCCA tools have been developed to help decision makers to perform LCCA easier and to make more informed decisions by better understanding each project's future maintenance and replacement requirements. Most of the current LCCA tools are spreadsheet based. Although most of the potential users are familiar with spreadsheet calculations, spreadsheet-based LCCA software programs can be quite limited due to the following reasons: 1) Inputting data for each individual scenario can be very labor intensive, 2) No online resources or databases will be available when using off-line spreadsheet-based models, 3) Usually not capable for performing complicated and computationally demanding calculations involving stochastic user or society costs. In order to overcome these limitations, NYU team developed a highly interactive web-based tool.

A.3 LCCA general cost function and implementation procedure

Project-level LCCA is performed by summing up the monetary equivalent of all benefits and costs at their respective time of occurrence and are converted into a common time dimension so that different alternatives can be compared correctly. A general expected life-cycle cost up to time, T, of known conventional material, LCC(T), can be expressed as below:

$$\mathrm{LCC(T)} = \mathrm{CC} + \mathrm{CM(T)} + \mathrm{CR(T)} + \mathrm{CU(T)} + \mathrm{CS(T)} + \mathrm{SV} \qquad \text{(Eq. A.1)}$$

where LCC is the Life-Cycle Cost (dollars), CC is the Construction Cost (dollars), CM is the Maintenance and repair Cost (dollars), CR is the Rehabilitation Cost (dollars), CU is the User Cost (dollars), CS is the Socio-economic Cost (dollars), SV is the Salvage Value (dollars), T is the Time (year).

Figure A.1 illustrates the objective function of LCCA and its general input parameters, as well output cost components at the project level.

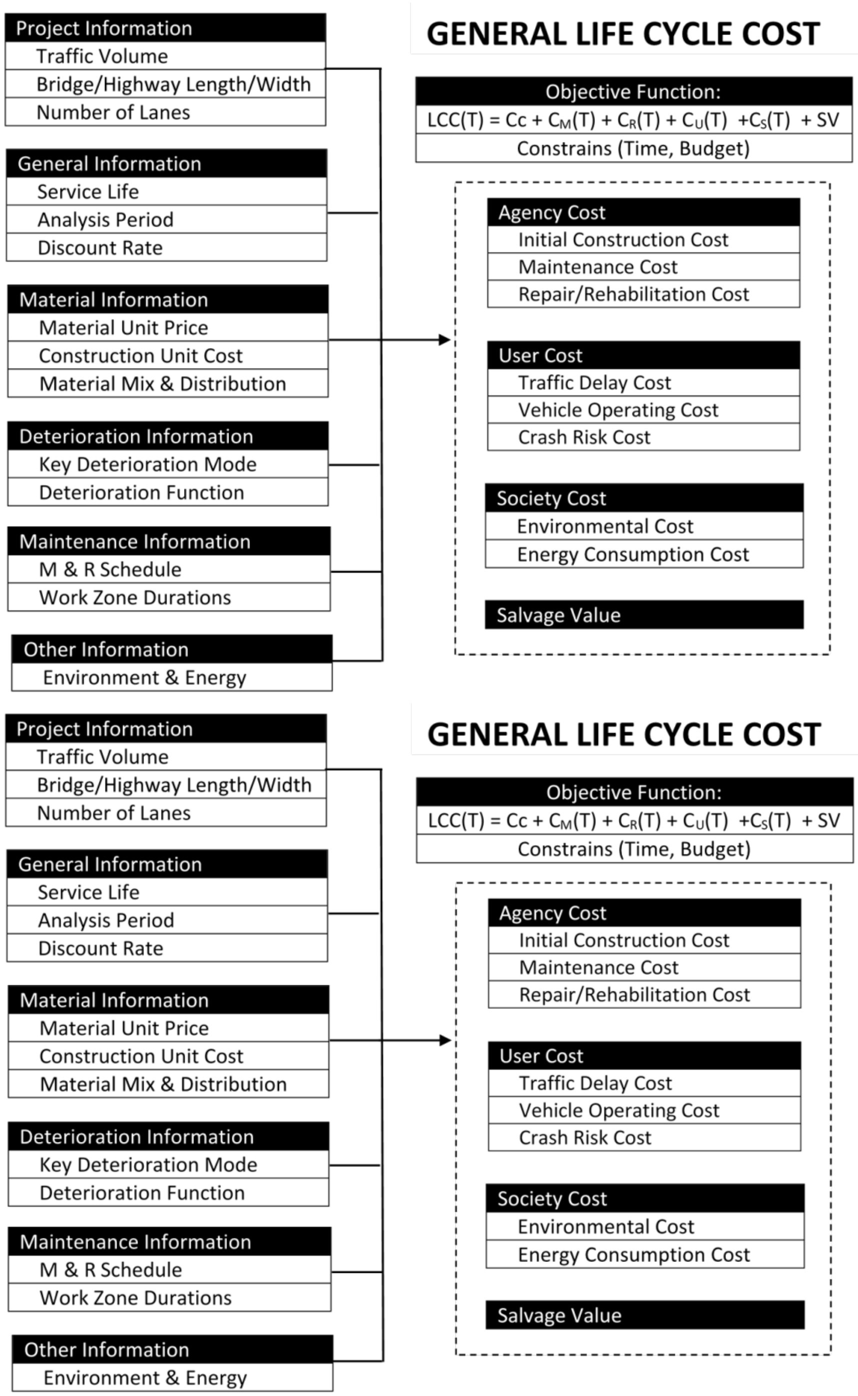

Figure A.1 General LCCA inputs and outputs (Ozbay and Gao, 2016)

Life-cycle and expenditure stream diagrams shown below (Figure A.2) illustrate the cost timeline of two alternatives. For the transportation infrastructure, this usually includes the initial construction cost, the maintenance and rehabilitation costs, the costs encountered by the user and the society, and the salvage value.

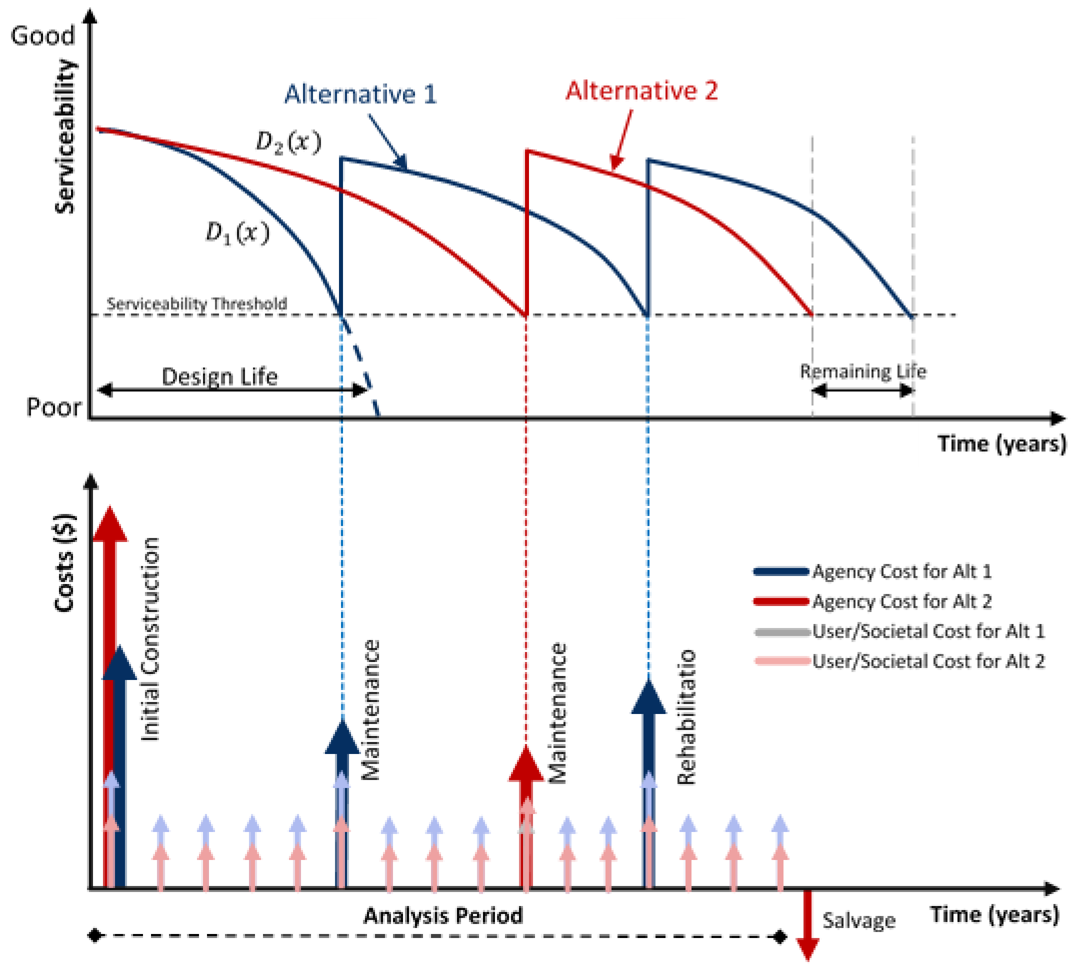

Figure A.2 Life-cycle of two alternatives and corresponding expenditure stream diagram (Jawad 2003)

After constructing the expenditure stream, computing the life-cycle cost (i.e., using Net Present Value (NPV) method) of each alternative becomes a straightforward calculation. It is advisable to compute agency, user, and society costs in a separate manner, before computing the total life cycle cost, to better understand the exact contribution of each cost category to the total final worth (Jawad 2003). Generally, an alternative is preferred if its NPV is less a minimum of 10% than the NPV of other competing alternatives (Jawad 2003). If the NPV difference between two alternatives is less than 10%, then such alternatives are considered similar or equivalent.

As most of the LCCA parameters, such as discount rate, traffic growth rate, and material unit cost, are uncertain, these uncertainties demand the use of a probabilistic approach to accurately quantify LCCA. By identifying and addressing those uncertainties, a reliable probabilistic life-cycle cost analysis can thus be performed. The probabilistic approach is strongly recommended in the case tackled by this project because the cost and technical performance of new-technology and /or materials are highly uncertain.

A.4 Deterioration models

Deterioration models are used to predict future conditions and to trigger preservation work based on the conditions. In order to perform a LCCA, one needs data and models about the deterioration process. One of the major factors in a reliable LCCA is the availability of accurate predictive models that describe the future deterioration rate of the transportation infrastructure. In brief, deterioration is a function of environmental effects and structural loading and involves various factors in LCCA. It is usually influenced by:

- Material type
- Construction techniques
- A mixture of material type and construction techniques
- External factors such as number of freeze/thaw cycles, amount of salt used, traffic demand and loads and etc.
- Maintenance factors such as type and frequency of maintenance treatments

Generally, the rate of deterioration is expected to gradually increase with time. That is to say, the operating condition is expected to decrease with time. The condition of the infrastructure is restored after maintenance and repair activities and then starts to deteriorate again, though it may be at a different deterioration rate, based on the material type and construction technology used in the maintenance and repair stages. A typical deterioration curve is shown at the upper portion of Figure A.3. By monitoring the specific infrastructure element's condition, the expected service life, defined as the number of years when its condition reaches a predefined threshold such as minimum acceptable operating condition, can be estimated. The shape of the deterioration curve relies on various condition states. Once the deterioration model is fed into the life cycle cost expenditure stream diagram (Figure A.3), it determines when to perform maintenance and repair activities. Then, their associated costs can be computed accordingly.

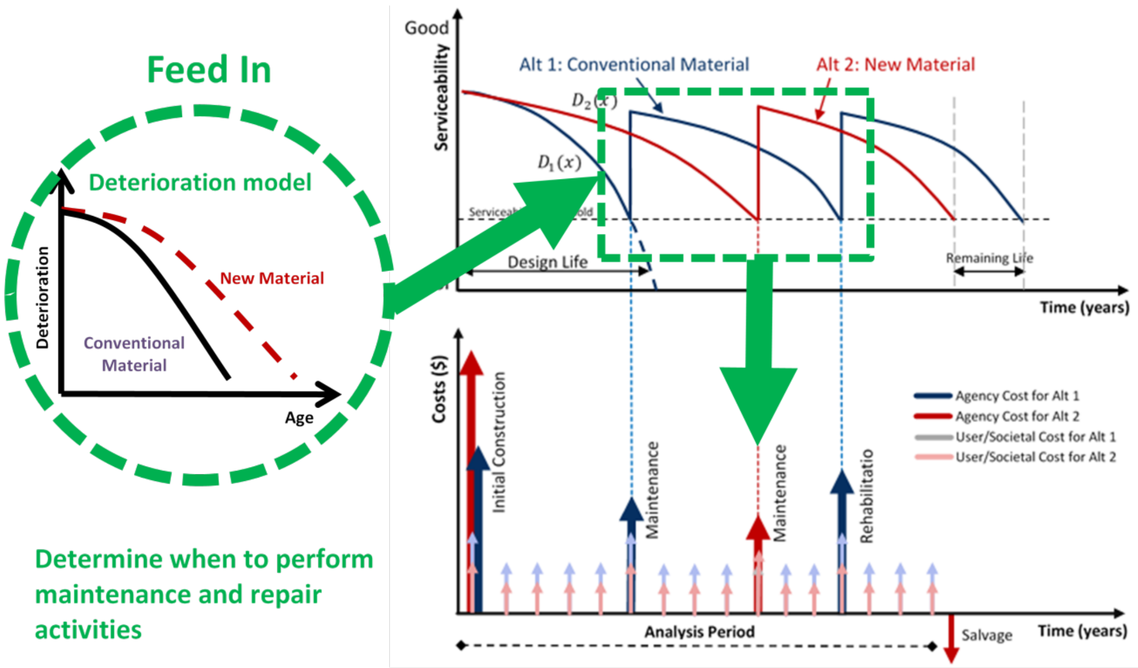

Figure A.3 Deterioration model and life cycle cost expenditures

A.5 Proposed methodology

Clearly, it is not a trivial task to predict the actual field performance of a new construction material or technology that has either only been tested in a laboratory environment or has undergone a very limited field deployment. Its performance prediction must thus rely on these limited laboratory tests or deployment results combined with expert opinion for the most likely values of its behavior under real-world conditions. This approach increases the uncertainty of such predictions. As a result, these uncertainties demand the use of a probabilistic approach to appropriately apply LCCA. Furthermore, the fact that these uncertainties can also vary in time creates the need for a robust stochastic treatment of the individual scenarios that will be evaluated as part of the proposed LCCA methodology.

It is not easy to predict the field performance of such materials due to lack of minimum amount of data. As more information and field data become available, the proposed approach should be re-evaluated and improved.

In light of all these complications, two different approaches are proposed: 1) Apply a hypothesized improvement rate to the deterioration functions of existing and well-known materials to represent the expected enhanced performance of a new material compared with a conventional material with relatively similar characteristics; 2) Utilize the correlation function between the results of laboratory tests and field performance of known materials to predict the expected performance of a new material based only on its laboratory tests. Figure A.4 shows the flowchart of these two proposed approaches.

A.5.1 Approach I – Improvement rate

Novel construction materials or technologies are expected to offer improvements, such as extended service life, compared with conventional materials or technologies. This approach is proposed to estimate the expected improvement rate of new materials or technologies by comparing them to conventional materials or technologies via laboratory tests.

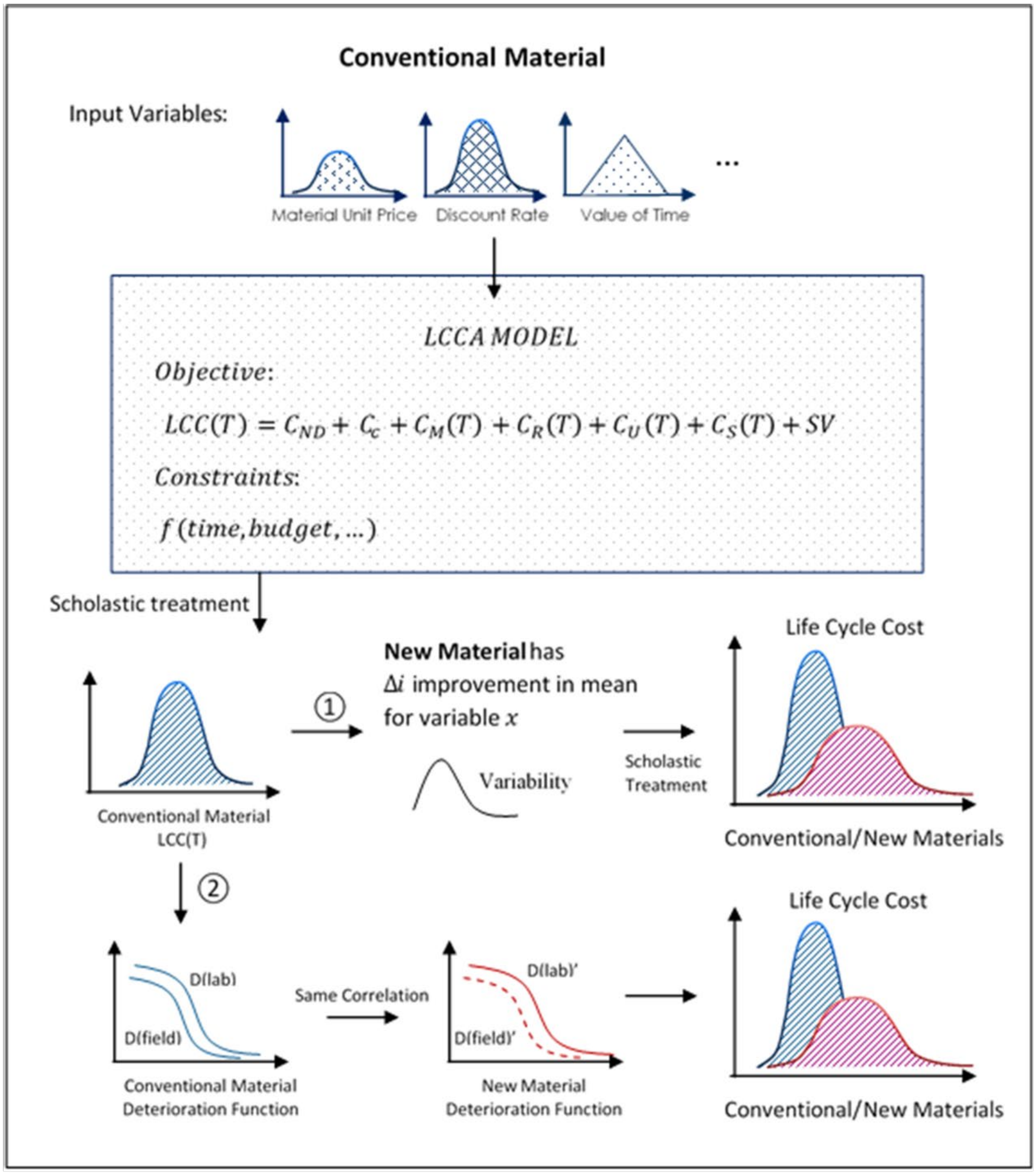

Figure A.4 Two proposed approaches for estimating predicted deterioration functions of a new material or a novel construction technology

Deterministic Approach

Estimated values or models based on historical data are often used as input to life-cycle analysis when quantifying costs. However, for a new material or construction technology, there may not be adequate data to accurately describe its real-world performance. An interim solution is to define metrics for the new material or technology as a percent improvement rate with respect to a current conventional material or technology with a known performance function. Then, this percent improvement rate is applied deterministically (or probabilistically) to this known performance function.

A new material is herein taken as an example. The relationship between this new material's deterioration function and conventional deterioration function is expressed using the equation below. It is assumed that the deterioration function of the new material will follow the same "shape" as that of the well-known conventional material. However, this shape will be shifted to represent the enhanced performance of the new material. Figure A.5 shows an example that turns results from laboratory tests into the improvement rate by employing this approach. The laboratory improvement rate, which is denoted by β, can be a single fixed value that is most likely to occur when using the deterministic approach. The correction factor, k, is applied to generate estimates when applying laboratory improvement rate to field.

$$F(x) = k \cdot f(\beta x) \tag{Eq. A.2}$$

where F(x) is the new material deterioration function, f(x) is the conventional material deterioration function, β is the laboratory improvement rate, k is the correlation factor.

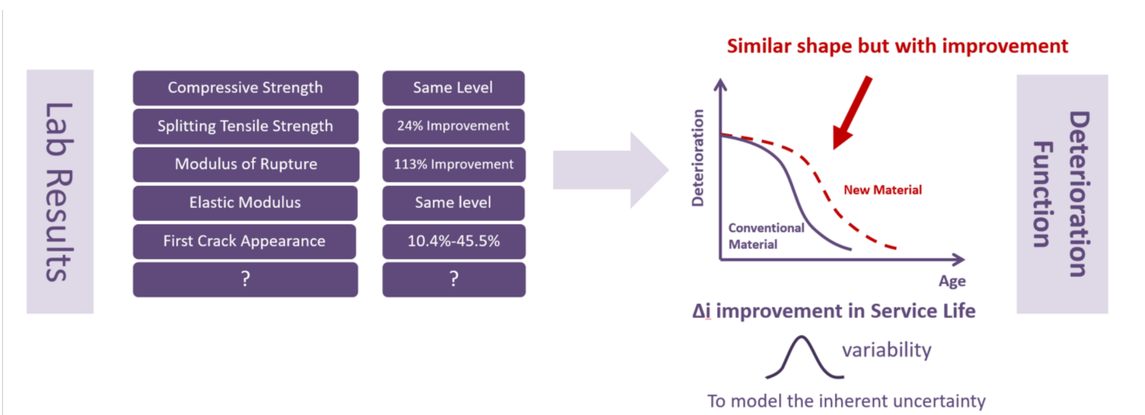

Figure A.5 Using laboratory results to update a deterministic deterioration function

Probabilistic Approach

LCCA has many variables in its objective function that might be difficult to predict with certainty even in the case of the well-known materials/situations. Usually, time-sensitive variables such as "discount rate" or "loads" are treated as random variables. However, in the cases of new materials and /or innovative construction technologies that have never been field tested or that have been recently deployed, the need for capturing uncertainties can be even more important. The goal is to determine how this stochasticity affects the sensitivity or prediction reliability of the total life-cycle cost of each alternative. Many techniques, such as Monte Carlo simulation and Latin Hypercube method, can be applied to quantify the effect of uncertainty propagating from non-deterministic variables. The aim of such treatment is to repeatedly generate random samples from one or more given probability distribution(s), each representing a specific variable, and to estimate the expectation of the total life-cycle cost for these specific distributions. Probabilistic LCCA can be performed according to the following steps:

- Decide on the operation level: Network-level or Project level?
- Determine LCCA objective and alternatives.
- Identify general project information, construction type, and road type.
- Determine timing of required activities.
- Determine the input parameters that carry inherent variability in their values that will be treated probabilistically in the study.
- Identify or develop a probability distribution that most closely matches the available data, or best represents current state of knowledge.
- Perform scholastic treatment (e.g. Monte Carlo simulations) to assign random values to the input parameters from a selected probability density function.
- Decide the number of iterations and convergence tolerance. Each iteration will result in a value for the life-cycle cost, and these values will be used to construct the probability distribution of the final outcome. Enough iterations should be performed until the simulation converges and any additional iteration has little effect on the final distribution.
- Evaluate and interpret the outcome - the probabilistic distribution of total life-cycle cost.

After implementing the stochastic treatment described above, the final outcome will be a probability distribution or a cumulative probability distribution of the life-cycle costs for each alternative (Figure A.6). Generally, wide distributions indicate high uncertainty in the parameter values while narrower distributions indicate less uncertainty.

A.5.2 Approach II – Correlation method

There have been some recent research efforts conducted to develop "performance tests" that can link the performance of parameters measured in the laboratory to actual field pavement or bridge performance (Dave 2011). This proposed approach is focused on such a correlation methodology between the laboratory test results and the available correlation values from published data, based on the actual field performance. If a correlation function between laboratory and field performance of a well-known material exists, one can assume that this relationship will remain the same for the new material as well. This same correlation function can be used to estimate the field performance of new material. This correlation function may include coefficient of thermal contraction, Poisson's ratio, complex modulus, resilient modulus, relaxation modulus and so on.

The functional specifications of the known deterioration function of conventional material and estimated deterioration function of new material are depicted using the following equations:

$$D(f_c) = D(l_c) \times f_{corr} \qquad \text{(Eq. A.3)}$$

$$D(f_n) = D(l_n) \times f_{corr} \qquad \text{(Eq. A.4)}$$

where D(f_c) is the field deterioration of conventional material, D(l_c) is the laboratory deterioration function of conventional material, D(f_n) is the field deterioration of new material, D(ln) is the laboratory deterioration function of new material, f_{corr} is the correlation function of model.

Suppose the comparison of a known conventional material M1 that has some similar characteristics with the proposed new high-performance material M2. If the laboratory deterioration function D(ln) is known for the proposed new material, M2, a field deterioration function D(fn) from the correlation function f_{corr} can be inferred (5.6).

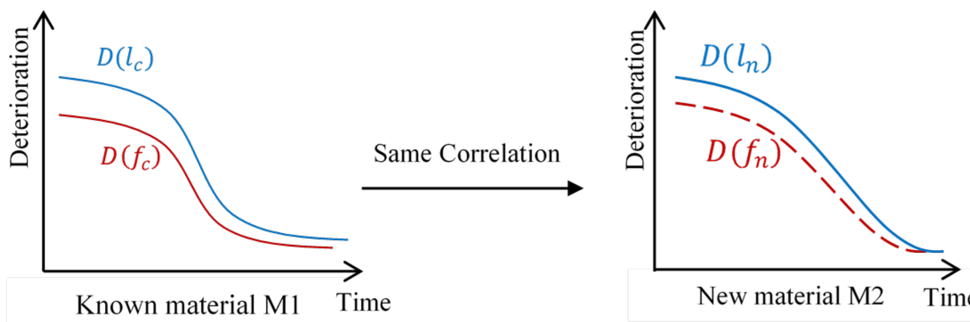

Figure A.6 Illustration of the proposed correlation method to quantify time-dependent deterioration behavior of new and known materials

A.6 LCCA example: economical and crack-free high performance concrete (Eco-HPC)

The following section illustrates the application of the LCCA approach to this project, the Economical and Crack-free High Performance Concrete with Adapted Rheology developed by Missouri University of Science and Technology (Missouri S&T) [1]. Eco-HPC concrete can be applied to pavement, bridges, and other infrastructures with relatively high resistance to early-age shrinkage cracking. Two classes of Eco-HPC are designed for the following applications: HPC for pavement construction (Eco-Pave-Crete) and HPC for bridge deck and transportation infrastructure construction (Eco-Bridge-Crete). Both HPC mixtures should develop high

[1] Email correspondence with Missouri S&T: 7/24/2016-Received Project Survey; 7/30/2016-Received additional Information about performance measures; 11/4/2016-Received information about shrinkage and structural performance of large elements; 11/22/2016-Received service life information of current Missouri bridge decks; 2/21/2017-Received supplemental information about Missouri pavement and bridge; 3/6/2017-Received energy consumption and global warming potential information.

resistance to early-age cracking to limit the crack width to hairline cracks as 0.1 mm (0.004 in.). The rheological properties of these advanced materials will be designed to facilitate construction operations and reduce labor and cost. Both Eco-HPC types will also be designed to ensure high durability. The following highlights potential improvements of the Eco-HPC concrete compare with typical MoDOT mixture (1).

- Decrease of construction time, labor, and equipment needed on construction sites
- Extend the time of crack initiation, crack propagation, and better durability aspects
- Significant noise reduction: Little or no vibration required
- Improved health and safety
- CO2 emission reduction from 745 kg/ton to 540 kg/ton
- 50% lower embodied energy consumption and 50% lower global warming potential

Hypothetical LCCA examples for bridge deck and pavement are built, based on this information using the improvement rate approach introduced in the previous sections.

A.6.1 User & societal costs

In this example, only the differential user and societal costs that are expected to occur during work zone periods are computed. Note that although including user costs is noted as a best-practice by the FHWA, it could greatly dominate total life-cycle costs, especially in the case of urban projects. It is suggested by the Illinois Department of Transportation (IDOT) (Holland 2012) to use a weighted factor (0.3 in this example) for the user cost when calculating the total life cycle cost.

A.6.2 Energy consumption and global warming potentials (GWPs)

The incorporation of high volume supplementary cementitious materials (SCMs) can contribute to significant reductions in CO2 emissions and embodied energy. The optimal concrete mixtures develop 40% lower embodied energy consumption and GWPs for the pavement application and 55% lower embodied energy consumption and GWPs associated with material manufacturing, transportation, and concrete production with respect to the MoDOT reference mixture (Mehdipour 2016). Using recycled steel wires that are recovered from scrap tires can also be effective in reducing pollution resulting from the manufacturing of brand new steel fibers. As one type of economic evaluation that can be carried out as part of conducting LCCA, cost-effectiveness analysis (CEA) can be a useful concept to evaluate energy consumption or emission reduction strategies, not only based on their reduction potential, but also based on the relative cost of that reduction. The following equation provides the basic relationship between costs, emissions, and cost-effectiveness (CE) (Santero, Loijos, and Ochsendorf 2013). The same method can be applied to energy consumption as well. The “new” and “con” subscripts refer to the new technology/material alternative and conventional technology/material case, respectively.

$$CE_{new} = \frac{\cos t_{new} - \cos t_{con}}{emmisions_{new} - emmisions_{con}} = \frac{\Delta \cos t_{new-con}}{\Delta emmision_{new-con}} \quad \text{(Eq. A.5)}$$

Figure A.7 shows the variation in primary energy consumption (PEC) and global warming potential (GWP) with different mixtures (Mehdipour 2016). By applying equation (A.5) for GWP reduction strategies, the cost-effectiveness of alternative A2, the optimized mixture for bridge, is 0.11 ($/lb CO2 -eq reduced), meaning that the new alternative A2 would cost $0.11 for every pound of carbon dioxide equivalent reduced. For the alternative B2, the optimized mixture for pavement, the cost-effectiveness is estimated as 0.23 ($/lb CO_2 -eq reduced). Similarly, for energy consumption reduction strategies, the cost-effectiveness values for alternatives A2 and B2 are estimated as 21.40 ($/giga joule, GJ, reduced) and 63.64 ($/GJ reduced), respectively.

Table A.3 presents the input information. The traffic data is obtained from one of the I-80 highway section in New Jersey, 0.7 miles east of Passaic River, for demonstration purposes only. For bridge deck, the estimated improvement rate of the Eco-Bridge-Crete service life is based on a combination of compressive strength, modulus of elasticity, shrinkage, durability factor, and cracking resistance laboratory improvement and large-scale structural performance. It is applied to Stage 1 (conditional rating 9-6) of deck deterioration as the Eco-Bridge-Crete mixtures will significantly increase the crack and propagation resistance, toughness, and long-term durability. For the pavement, the estimated improvement rate is based on a combination of compressive strength, modulus of elasticity, bulk resistivity, shrinkage, durability factor, and cracking resistance laboratory improvement. It is applied to both service life and rehabilitation extended service life. A 20% saving in labor cost is assumed when estimating the construction unit cost of the new material in both cases. These values will be further evaluated once field implementation data becomes available. The deterministic LCCA output is shown in Table A.7. Besides agency cost, traffic delay, vehicle operating, crash risk, and air pollution costs are included in this example as well.

A.6.3 Agency costs

In this example, agency costs include initial construction, maintenance, and rehabilitation costs as well as the salvage value. For the bridge deck, the rehabilitation cost can be broken down into four categories (NJDOT 2015): a) the cost of replacing the structure (include demolition and traffic control), b) approach roadway work, c) traffic staging and d) preliminary engineering. Rehabilitation cost is assumed to be 1.8 times the new bridge initial construction cost. Maintenance cost is assumed to be 5% of the initial construction cost. For pavement, miscellaneous mobilization, and preliminary engineering costs are assumed to be 20%, 5%, 9.5% for initial construction and 9.5%, 1.9%, 9.5% for rehabilitation (Missouri Department of Transportation 2004), respectively. Maintenance costs for both pavement alternatives are assumed to be the same over the entire design lives so they are not inputted into the LCCA for the pavement example. Salvage value is the value of an investment alternative at the end of the analysis period. This is usually included as a benefit or negative cost in agency cost.

Table A.3 LCCA example work flow – inputs

I. Analysis options	Alt A1: Conventional Concrete Bridge	Alt A2: Eco-Bridge-Crete	Alt B1: Conventional concrete pavement	Alt B2: Eco-Pave-Crete
1. Service life (years)	45	60	25	33
2. Analysis period (years)	75	75	45	45
3. Discount rate (%)	3.0%	3.0%	3.0%	3.0%
4. Material unit price ($/CY)	72*	94*	45*	66*
5. Construction unit cost (bridge deck: $/SF, pavement: $/SY)	114.17*	128.00	53.00*	69.56

II. Traffic data	Alt A1: Conventional Concrete Bridge	Alt A2: Eco-Bridge-Crete	Alt B1: Conventional concrete pavement	Alt B2: Eco-Pave-Crete
Average daily traffic (veh/day):	114,739	114,739	114,739	114,739
Trucks as percentage of ADT (%):	1.55%	1.55%	1.55%	1.55%
Annual growth rate of traffic (%):	0.5%	0.5%	0.5%	0.5%
Lanes opened under normal condition:	Inbound (4), outbound (5)	Inbound (4), outbound (5)	Inbound (4), outbound (5)	Inbound (4), outbound (5)
Value of time ($/hr):	11.58 (Passenger car), 20.43 (Truck)	11.58 (Passenger car), 20.43 (Truck)	11.58 (Passenger car), 20.43 (Truck)	11.58 (Passenger car), 20.43 (Truck)

III. Work zone input	Alt A1: Conventional Concrete Bridge	Alt A2: Eco-Bridge-Crete	Alt B1: Conventional concrete pavement	Alt B2: Eco-Pave-Crete
Maintenance schedule:	Every 5 years	Every 5 years	Maintenance schedule/cost are assumed to be the same for both alternatives and are neglected in this study	Maintenance schedule/cost are assumed to be the same for both alternatives and are neglected in this study
Rehabilitation/replacement schedule:	Every 45 years	Every 60 years	Time to first rehabilitation: 25 years (rehabilitation extended service life: 20 years)	Time to first rehabilitation: 33 years (rehabilitation extended service life: 26 years)

III. Work zone input	Alt A1: Conventional Concrete Bridge	Alt A2: Eco-Bridge-Crete	Alt B1: Conventional concrete pavement	Alt B2: Eco-Pave-Crete
Maintenance duration (days):	10	10	N/A	N/A
Rehabilitation duration (days):	120	108	30	27
# lanes opened during maintenance/rehab:	2 lanes/1 lane	2 lanes/1 lane	2 lanes	2 lanes
Free flow speed (mph):	70	70	70	70
Work zone speed-maintenance (mph):	50	50	50	50
Work zone speed-rehabilitation (mph):	30	30	30	30

IV. Conclusions	Estimated improvement rate based on laboratory results
Bridge deck	Since the Eco-Bridge-Crete mixtures will significantly increase the crack and propagation resistance, higher toughness, and long-term durability, the research team applied the estimated improvement rate 50% to Stage 1 (rating 9-6) of deck deterioration.
Pavement	The research team applied the estimated improvement rate 30% to both service life and rehabilitation extended service life.

*Price reference: (FHWA 2011, Mehdipour 2016)

Table A.4 LCCA example work flow – deterministic outputs

I. Agency cost ($)	Alt A1: Conventional Concrete Bridge	Alt A2: Eco-Bridge-Crete
Initial construction cost ($):	3,108,020	3,484,505
Maintenance cost ($):	852,457	955,718
Rehabilitation cost: (A) Replace the structure ($):	1,083,799	779,915
Rehabilitation cost: (B) Approach roadway work ($):	68,520	38,996
Rehabilitation cost: C) Traffic staging ($):	287,783	163,782
Rehabilitation cost: (D) Preliminary engineering ($):	143,892	81,891
Total rehabilitation cost (s):	1,479,385	1,064,585
Salvage value ($):	-203,162	-512,487
Total agency cost ($):	$5,236,700	$4,992,321

I. Agency cost ($)	Alt B1: Conventional concrete pavement	Alt B2: Eco-Pave-Crete
Initial construction cost ($):	322,748	355,396
Maintenance cost ($):	Maintenance cost is assumed to be the same for both alternatives and is neglected in this study	Maintenance cost is assumed to be the same for both alternatives and is neglected in this study
Rehabilitation cost: (A) Slab replacement (1.5%) ($):	7,430	5,958
Rehabilitation cost: (B) Treatment -diamond grinding ($)	6,896	5,444
Rehabilitation cost: (C) Miscellaneous & mobilization ($)	2,067	1,645
Rehabilitation cost: (D) Preliminary engineering($)	1,723	1,371
Total rehabilitation cost (s):	18,116	14,419
Salvage value ($):	0	-39,871
Total agency cost ($):	$340,864	$329,945

II. User cost ($)	Alt A1: Conventional Concrete Bridge	Alt A2: Eco-Bridge-Crete
Traffic delay cost ($):	$25,732,076	$19,216,750
Vehicle operation cost ($):	$1,727,985	$1,280,384
Crash risk cost ($):	$25,153	$15,659
Total user cost ($):	$25,161,738	$20,512,793

II. User cost ($)	Alt B1: Conventional concrete pavement	Alt B2: Eco-Pave-Crete
Traffic delay cost ($):	$1,387,082	$1,281,998
Vehicle operation cost ($):	$117,318	$100,305
Crash risk cost ($):	$10,279	$7,600
Total user cost ($):	$1,514,679	$1,389,903

III. Social cost ($)	Alt A1: Conventional Concrete Bridge	Alt A2: Eco-Bridge-Crete
Air pollution cost ($):	$7,307	$4,549
Total social cost ($):	$7,307	$4,549

III. Social cost ($)	Alt B1: Conventional concrete pavement	Alt B2: Eco-Pave-Crete
Air pollution cost ($):	$2,986	$2208
Total social cost ($):	$2,986	$2,208

IV. Life cycle cost	Alt A1: Conventional Concrete Bridge	Alt A2: Eco-Bridge-Crete
Total life cycle cost:	$13,489,571	$11,256,927
Benefit:		**Total life cycle cost: -17.34%** **Agency cost: -4.67%, user cost: -25.37%, social cost: -37.74%** (user cost factor: 0.3, social cost factor: 1.0)

IV. Life cycle cost	Alt B1: Conventional concrete pavement	Alt B2: Eco-Pave-Crete
Total life cycle cost:	$798,254	$749,123
Benefit:		**Total life cycle cost: -6.15%** **Agency cost: -3.20%, user cost: -8.24%, social cost: -26.06%** (user cost factor: 0.3, social cost factor: 1.0)

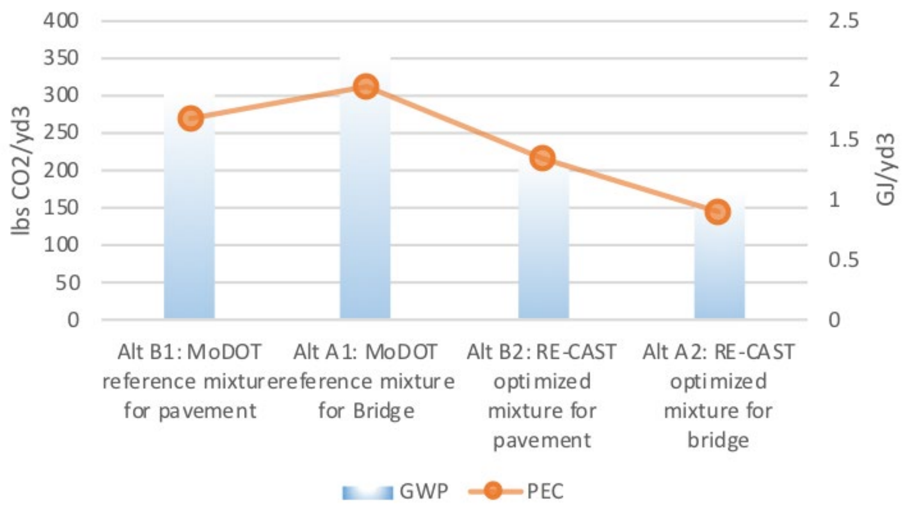

Figure A.7 Variation in embodied energy and GWP with different mixtures (Mehdipour 2016)

The final deterministic LCCA results, given in Table A.4, show that the application of the new material will save 4.67% of agency costs and 17.34% of total life cycle cost for the bridge deck, and will save 3.20% of agency cost and 6.15% of total life cycle cost for the pavement. If only agency costs are evaluated, alternatives can be considered similar or equivalent because the difference between agency costs of alternatives is less than 10%. However, the benefit in user costs especially in the case of the bridge deck rehabilitation/replacement and potential energy consumption and GWP savings play an important role and should not be ignored. On the other hand, sensitivity analysis should be conducted if the deterministic approach is adopted in conducting LCCA. The sensitivity analysis will be able to examine the effect of the variability in the main input parameters and can be accomplished by performing the analysis over a range of possible values of the same input parameter being tested while holding all other parameters constant (Jawad 2003). Figure A.8 shows the results of the sensitivity analysis of applying different user cost weights in the bridge deck example.

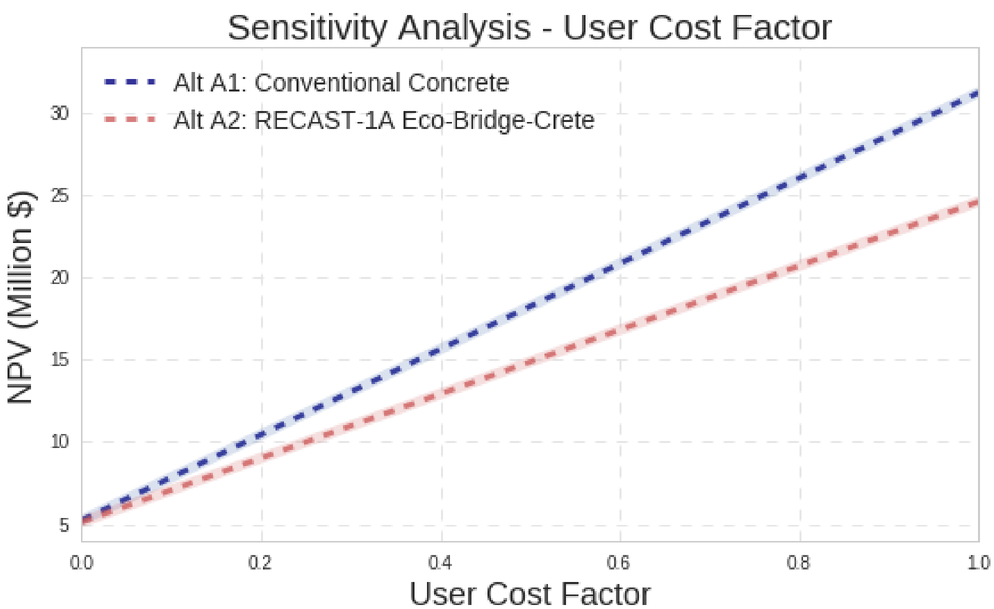

Figure A.8 Sensitivity analysis of net percent value (NPV) with applying different estimated weights of user cost

In contrast to the deterministic approach, probabilistic approach (Figure A.9) provides additional capabilities that allow the analyst to quantify parametric variation and uncertainty. Moreover, instead of fixed LCC values, the output can be represented as probabilistic distributions. The following figure shows the total life cycle cost of two alternatives for the bridge deck application. Let's assume that the construction cost for the alternative A1 conventional material follows a normal distribution N (114.17, 5) and the construction cost for the alternative A2 follows a normal distribution N (128.00, 30. After randomly sampling from these probability distributions using Monte Carlo simulation, the final life cycle cost analysis results indicate that the Alternative A2, namely Eco-Bridge-Crete is less expensive (10.21 million dollars) compared with the Alternative A1, namely, conventional concrete (12.63 million dollars) in terms of their mean values. However, Alternative A2 has also more uncertainty due to a standard deviation of $0.93 million compared to that of the conventional material which is $0.19 million. One can determine, the likelihood of the Alternative A2's average life cycle cost being more than that of the Alternative A1 and decide which alternative to use based on these probabilities. Moreover, different probability functions can be used to study the sensitivity of LCC's uncertainty. Clearly, probabilistic LCCA provides us with an approach that is more versatile and comprehensive than the deterministic LCCA when it comes to making long-term decisions in the presence of a number of uncertainties that cannot be easily ignored.

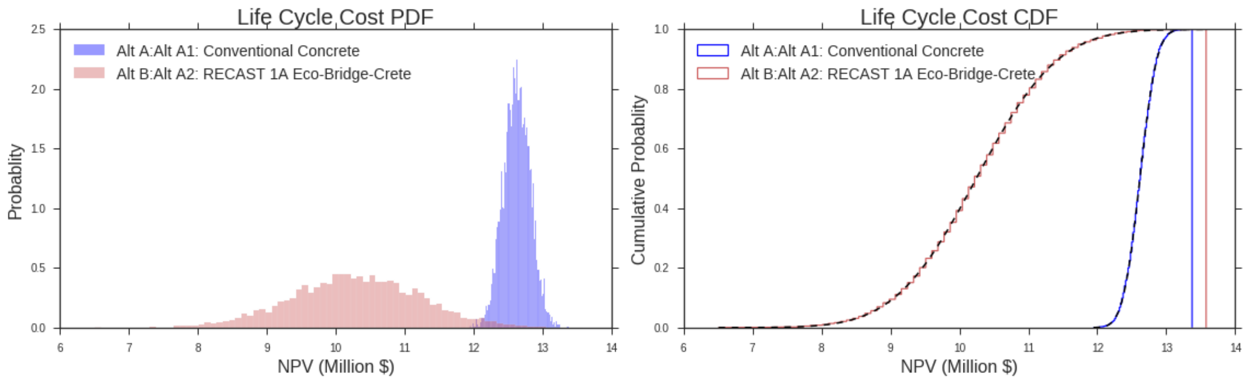

Figure A.9 Bridge LCCA example – probabilistic approach