Sustainable Long-Life Composite Concrete Pavement for the Illinois Tollway

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ABSTRACT

The Illinois State Toll Highway Authority (Tollway) has begun the 15-year, multi-billion dollar Move Illinois program for roadway reconstruction, rehabilitation, and expansion. To improve sustainability efforts, the Tollway initiated a study conducted at the University of Illinois to investigate the changes in fresh and hardened properties when using coarse, fractionated (separated by size) reclaimed asphalt pavement (FRAP) as a partial replacement of virgin coarse aggregate in a ternary blended concrete for rigid pavement. The coarse FRAP replacement levels were 0, 20, 35, and 50% of the coarse aggregate content in a mix. The results indicated that acceptable strength properties can be attained with up to 50% FRAP addition, and extra processing of the "dirty" FRAP by washing to produce a "clean" FRAP didn't significantly improve these properties. Additionally, matching the clean FRAP gradation to the typical virgin coarse aggregate gradation yielded statistically insignificant differences in strength properties. Another part of this study demonstrated that concrete with FRAP can have suitable durability properties.

From these preliminary findings, and to enhance sustainability efforts, the Tollway developed performance-based specifications for ternary concrete mixes with a coarse aggregate content containing between 20% and 50% dirty FRAP, as well as specifications for the construction of two-lift concrete pavements for the use of such mixtures in the bottom lift. Based on the FRAP concrete properties, a two-lift concrete pavement section was designed using DARWin-ME. Additional design inputs included the expected local climate, traffic, materials, and pavement structure specific to the Illinois Tollway. The resultant 12- to 14-inch dowelled concrete pavement design consists of a 9.0- to 11.0-inch bottom lift containing FRAP and a 3.0-inch top lift of virgin aggregate concrete and 15-foot joint spacing. A life cycle cost analysis of the two-lift composite concrete shows no difference from a standard jointed plain concrete section due to the engineering properties of the two-lift concrete and the construction cost estimates.

Key words: Reclaimed asphalt pavement, RAP, fractionated reclaimed asphalt pavement, FRAP, recycling, ternary concrete, sustainability, green concrete, long-life pavement, concrete pavements, pavement design, DARWin-ME, Move Illinois program

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INTRODUCTION

In 2011, the Illinois State Toll Highway Authority (Tollway) initiated the 15-year, multi-billion dollar Move Illinois program aimed at rebuilding, rehabilitating, and expanding parts of the Tollway's road system. The Tollway will use long-life design principles for these pavement structures, which means a 30- to 40-year service life before the first major rehabilitation action. This paper summarizes the planning, research, and design for the composite two-lift concrete pavements with recycled materials that will be constructed through the Move Illinois program.

A primary component of Move Illinois is fully recycling the existing pavement materials. Tollway mainline asphalt overlays placed in the last two decades have required the use of high-quality coarse aggregates (same quality as required for concrete) and the use of only manufactured sands. All aggregates in existing Tollway mainline overlays come from sources with little if any history of generating alkali-silica reactivity issues in concrete. When existing asphalt pavements are milled and/or removed, reclaimed asphalt pavement (RAP) containing high-quality aggregates is produced. This RAP is then separated (or fractionated to produce FRAP) into fine and coarse sizes at the #4 sieve, and all large agglomerations not passing the maximum screen size, typically 1/2 inch or 5/8 inch, are discarded and not re-crushed. Recent research has found that both fine and coarse FRAP can be used successfully in the Tollway's hot-mix asphalt pavements (Vavrik et al. 2008). The Tollway has also been using fine FRAP as a percentage replacement of virgin asphalt binder when mixed in conjunction with reclaimed asphalt shingles (RAS).

The Tollway currently has numerous stockpiles of high-quality coarse FRAP and will be producing even more over the next 15 years. To investigate the use of coarse FRAP as a partial replacement of virgin coarse aggregate in concrete, the Tollway initiated a research project to determine the maximum replacement levels to meet current specification criteria. With the results from the research, the Tollway began planning field test projects and future composite pavement design and construction to utilize coarse FRAP in concrete pavements.

SUSTAINABLE PAVEMENT STRATEGIES FOR THE ILLINOIS TOLLWAY

In 2011, the Tollway's $12 billion dollar, 15-year program called Move Illinois was initiated to reconstruct, rehabilitate, and enlarge parts of the Tollway system. The Move Illinois program includes the reconstruction of more than 85 centerline miles of expressway pavement in the Chicago area (Figure 1). One of the Tollway's primary objectives is to reconstruct these pavements using the most sustainable options through balancing the construction project's economic, environmental, and societal impacts. To achieve this objective, the pavements will be reconstructed in a manner that reuses the existing pavement materials in the newly reconstructed pavement layers.

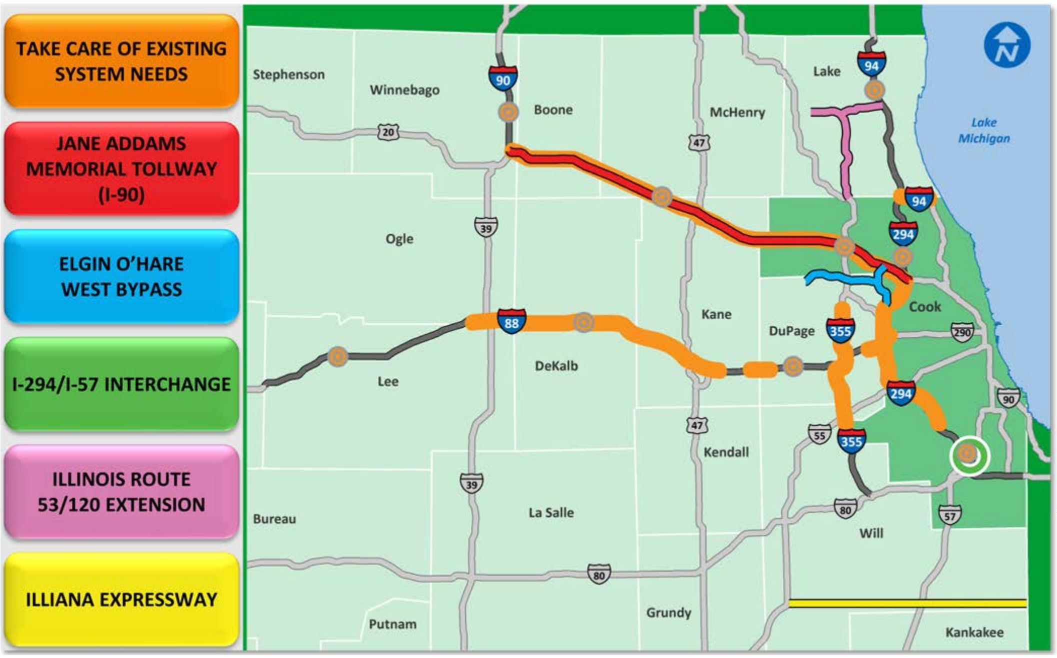

Figure 1. The Illinois Tollway system and future Move Illinois construction projects.

The Tollway has recently made advances in researching the performance of asphalt mixtures with high levels of recycled material content and using more sustainable construction techniques. With long-life asphalt pavements constructed over the last 5 years under the Tollway's previous construction program, recycling was increased by using ground tires as an alternative to polymer modifiers, RAS as both a substitute for fiber in stone-matrix asphalt mixes and as a substitute for virgin liquid asphalt in all other mixes, higher levels of FRAP in all asphalt mixes, and softer-grade liquid asphalts in all asphalt mixes to accommodate asphalt binder replacements ranging from 35% to 50% in binder and surface courses. New construction techniques and processes to improve the sustainability of Tollway asphalt pavements include the introduction of FRAP and the mandate to use warm mix asphalt technologies in 2012. Under the Move Illinois program, a large portion of the reconstructed and widened or newly constructed expressways will be long-life concrete pavement. As with the more sustainable asphalt mixtures and construction, the Tollway's goal is to increase concrete mixture recycling and improve overall sustainability of concrete pavements.

In addition to the availability of large quantities of high-quality coarse FRAP, the Move Illinois program will make use of existing concrete pavements as another recycled aggregate source for reconstructed and widened corridors. A large portion of the future reconstructed median miles consist of a 4-inch hot-mix asphalt overlay of 10-inch jointed reinforced concrete pavement over 10 inches of aggregate subbase. The reuse of the existing subbase material and external RAP sources with lower quality aggregates can allow for the existing concrete pavements to be available for coarse recycled concrete aggregate (RCA) for new concrete pavement mixes, and as porous RCA for part of the new subbase under the pavement. The residual fines from RCA processing can also be reused in cementitious flowable fill mixes to stabilize abandoned drainage structures and culverts. Supplementary cementitious materials (SCM) such as Class C fly ash and ground granulated blast furnace slag will be allowed so that contractors can supply ternary concrete mixes with at least 35% of the portland cement to be replaced with SCM in these future concrete pavements.

TOLLWAY CONCRETE WITH FRAP RESEARCH

Overview of Concrete Containing FRAP Investigations

Previous studies have found that RAP can have a significant effect on the hardened properties of concrete, resulting in reductions in the compressive, split tensile, and flexural strengths and the modulus of elasticity (Sommer 1994; Kolias 1996; Delwar et al. 1997; Sommer and Bohrn 1998; Dumitru et al. 1999; Hassan et al. 2000; Mathias et al. 2004; Huang et al. 2005, 2006; Hossiney et al. 2008, 2010; Al-Oraimi et al. 2009; Okafor 2010; Bermel 2011; Bilodeau et al. 2011; Brand et al. 2012a, 2012b). The Illinois Tollway has been investigating concrete mixtures cast with various replacements of washed FRAP and determining the corresponding fresh, hardened, durability, shrinkage, and fracture properties of the concrete (Brand et al. 2012b). Due to the additional costs of washing the FRAP, laboratory investigations have also studied the differences in FRAP processing, such as no processing, minimizing the percent passing the #4 sieve, or washing, as described below.

"Dirty" FRAP Study (Brand et al. 2012a)

Studies have been conducted at the University of Illinois, and other mixes have been evaluated by S.T.A.T.E. Testing, an independent testing laboratory, to determine the effects of a "dirty" FRAP on the fresh and strength properties of concrete (Brand et al. 2012b). Dirty FRAP has not been extensively field-processed (i.e., washed) so the FRAP may have an increased amount of particles passing the #4 sieve (21.9% passing the #4 for dirty FRAP versus 3.6% for the clean FRAP) and could have a higher asphalt content (3.3% asphalt for the dirty FRAP versus 2.1% for the clean FRAP). The results of these studies indicated that, like clean FRAP, dirty FRAP can be used successfully as a partial replacement of coarse virgin aggregate in concrete. Acceptable fresh properties can be attained with suitable air contents in the range of 5% to 8%. It was found that dirty FRAP contents up to 50% could be utilized and still meet the specified minimum compressive strength requirement of 3,500 psi at 14 days. Independent results from S.T.A.T.E. Testing indicated that up to 45% dirty coarse FRAP could be used even when using a lower cementitious content (600 lb/yd^3), and a mix combining 35% dirty FRAP and 65% recycled concrete aggregate could reach the specified 3,500 psi compressive strength requirement. An additional study found that processing the dirty FRAP in the laboratory to remove the particles passing the #4 sieve did not have a significant effect on the compressive and split tensile strengths, which indicates that reasonable FRAP gradations may not need additional processing in the field prior to concrete batching.

Previous RAP in Concrete Pavement Field Studies

There have been previous field studies utilizing RAP in concrete. In the early 1990s, an Austrian highway between Vienna and Salzburg was reconstructed using the crushed concrete roadway, which had a thin asphalt overlay (Sommer 1994). The final pavement consisted of a two-lift concrete construction with 21-cm bottom lift that had crushed concrete and 10% RAP (both were coarse aggregate retained on the 4-mm sieve) and a 4-cm top lift with an optimized virgin aggregate concrete. The fine aggregate from the crushing operation (passing the 4-mm sieve) was recycled into the granular subbase.

In 1997, the Kansas Department of Transportation constructed several two-lift concrete test sections on Highway K-96, one of which contained RAP (Wojakowski 1998). The bottom lift was 7 inches thick and contained 15% RAP (by weight of total aggregate) as a replacement of the intermediate-sized aggregate. The top lift was 3 inches of typical virgin aggregate concrete. In 2009, an evaluation of the concrete test sections revealed that the load transfer efficiency of the RAP test section was at 85% (McLeod 2010). The RAP test section had also slightly greater faulting (0.22 vs. 0.15 mm per joint) and spalling (83 vs. 67 mm per joint) than the control concrete section.

In October 2010, the Tolloway placed the first concrete pavement with RAP in Illinois, on an I-94 ramp for Milwaukee Avenue. The composite pavement section consisted of a 9-inch-thick concrete with coarse FRAP and a 3-inch hot-mix asphalt overlay. The concrete contained 655 lb/yd^3 of cementitious material with 79% cement and 21% fly ash and about 28% coarse FRAP.

FRAP in Concrete Laboratory Study

A review of past FRAP in concrete studies shows that researchers have not directly considered the effect of RAP gradation on the measured fresh and strength properties. Aggregate gradation is known to impact concrete workability and strength. The objective of the new laboratory study was to quantify the effects of coarse FRAP at different replacement levels with the same gradation on the fresh concrete properties and the compressive and split tensile strengths with a ternary blended concrete (containing cement, slag, and fly ash).

Aggregate Properties and Concrete Mix Design

This laboratory investigation examined four different washed, FRAP replacements: 0, 20, 35, and 50% by weight of coarse aggregate compared with mixtures cast with these same FRAP replacement levels but with approximately the same combined aggregate gradation. The FRAP source used in this study was from the Jane Addams Memorial Tollway (I-90), which had a 5/8 inch maximum aggregate size. The gradation and aggregate properties can be found in Table 1. By centrifuge extraction the asphalt content of the FRAP was found to be 2.1%. This FRAP had been washed in the field and was therefore considered a “clean” FRAP.

The mix designs for each FRAP content are presented in Table 2. The cementitious content was 630 lb/yd^3, which was a ternary blend consisting of 65% Type 1 portland cement, 25% Grade 100 ground granulated blast furnace slag, and 10% Class C fly ash. The water-to-cementitious ratio was held constant at 0.37. The mix designs were all formulated using the absolute volume methodology. The total amount of coarse aggregate decreased as the FRAP content increased, which was due to the decreasing blended coarse aggregate specific gravity. Two chemical admixtures were added: an air-entraining admixture (AEA) and a water-reducing admixture (WRDA).

Table 1. Aggregate properties and gradation.

	Washed FRAP	Virgin Coarse Aggregate	Virgin Fine Aggregate
Bulk Unit Weight, lb/ft^3 (kg/m^3)	93.4 (1,500)	96.9 (1,550)	112.1 (1,800)
Relative Specific Gravity (SSD)[1]	2.59	2.72	2.66
Absorption	2.45%	1.80%	1.47%
Asphalt Content	2.1%	-	-
Agglomerated Particles	14.2%	-	-
Gradation			
1" (25mm)	100.0%	100.0%	-
3/4" (19mm)	99.9%	96.2%	-
1/2" (12.5mm)	78.4%	36.5%	-
3/8" (9.5mm)	37.9%	11.1%	100.0%
#4 (4.75mm)	3.6%	1.3%	99.9%
#8 (2.36mm)	1.6%	1.1%	90.1%
#16 (1.18mm)	1.1%	1.1%	70.3%
#30 (0.6mm)	0.8%	1.1%	46.4%
#50 (0.3mm)	0.6%	1.0%	16.4%
#100 (0.15mm)	0.3%	0.9%	3.2%
#200 (0.075mm)	0.1%	0.7%	0.8%

[1] SSD = Saturated Surface Dry

Table 2. Concrete mix designs by FRAP content, in lb/yd^3 (kg/m^3).

	FRAP Content			
	0%	**20%**	**35%**	**50%**
Cement	409.5 (242.8)			
Slag	157.5 (93.4)			
Fly Ash	63.0 (37.4)			
Virgin Coarse Aggregate (SSD)	1,895.4 (1,124.0)	1,501.2 (890.2)	1,210.7 (718.0)	924.5 (548.2)
FRAP (SSD)	0.0 (0.0)	375.3 (222.6)	651.9 (386.6)	924.5 (548.2)
Virgin Fine Aggregate (SSD)	1,129.6 (669.9)			
Water	230.9 (136.9)			
AEA[1]	1.15 (0.75)			
WRDA[1]	4.5 (2.93)	4.3 (2.80)	4.25 (2.77)	4.25 (2.77)

[1] Listed as dosage of fluid ounces per 100 pounds cementitious (mL per 100 kg cementitious)

In this study two different concretes were tested using the same mix design. The first concrete used the stock gradation for each aggregate as shown in Table 1. The second concrete used a "matched gradation" in which the FRAP was re-graded to match the gradation of the virgin coarse aggregate. Since there was very little FRAP retained on the 3/4-inch sieve, this aggregate size was replaced by virgin coarse aggregate.

The concrete was mixed in a pan mixer following the procedure in ASTM C192 (2007). Several batches for each mixture were required to produce enough concrete to cast all the laboratory specimens. After the concrete was cast, it was covered with plastic and cured at ambient laboratory temperature for 24 hours, after which the concrete was removed from the molds and placed in a moist curing room until the testing age. The specimens were tested for compressive and split tensile strengths at 7, 14, and 28 days with 4- by 8-inch cylindrical specimens. The compressive and split tensile strengths were evaluated following AASHTO T22 (2007) and AASHTO T198 (2009), respectively.

Concrete with FRAP Matched Gradation Results

The fresh concrete properties for the specimens cast are shown in Table 3. In general, the mean air content was unaffected by the presence of FRAP in the concrete, although at higher FRAP contents the air content was more variable. The slump increased with FRAP content despite a reduction in the WRDA dosage. The unit weight decreased with increasing FRAP content, which is expected since the FRAP has a lower specific gravity.

Table 3. Concrete fresh properties.

Concrete Batch	FRAP Content	Air Content	Slump, inch (mm)	Unit Weight, lb/ft^3 (kg/m^3)
Compressive Strength	0%	7.2%	4 (100)	141.0 (2,259)
	20%	6.6%	5 (125)	141.4 (2,265)
	35%	7.5%	5.5 (140)	138.0 (2,211)
	50%	6.4%	3 (75)	141.2 (2,262)
Split Tension Strength	0%	4.2%	1.5 (40)	150.6 (2,412)
	20%	5.4%	2 (5)	147.0 (2,355)
	35%	5.8%	2.5 (65)	145.2 (2,326)
	50%	6.4%	2 (50)	143.8 (2,303)
Gradation Match	0%	6.8%	3 (75)	145.2 (2,326)
	20%	6.0%	2.5 (65)	145.0 (2,323)
	35%	6.0%	2.5 (65)	143.4 (2,297)
	50%	7.0%	4 (100)	139.4 (2,233)

The compressive and split tensile strengths for the stock gradations are shown Figure 2 and Figure 3, respectively. In general, the strength decreased with increasing FRAP content, as noted by other researchers, with the reduction split tensile strength slightly greater as FRAP content increased. The strength reduction is due to the insufficient bond between the FRAP particles and the cementitious matrix. Considering the Illinois Department of Transportation compressive strength requirement of 3,500 psi (24,000 kPa) at 14 days (IDOT 2012), it is evident that the 0, 20, and 35% FRAP mixes meet the requirement. The 50% FRAP was 0.3%

below the requirement, but at later ages (28 days), all mixes surpassed the 3,500 psi strength requirement.

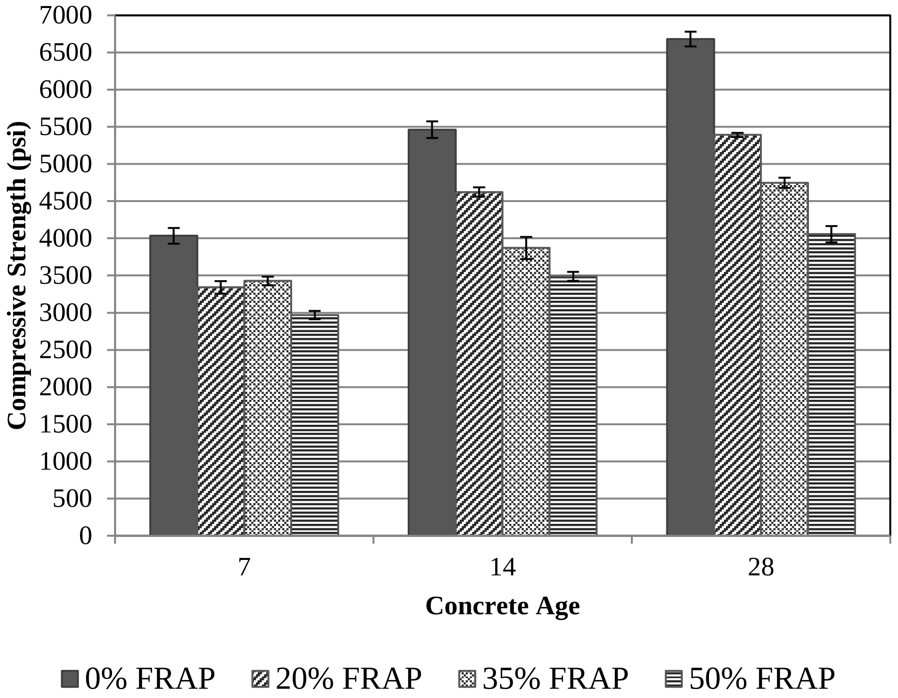

Figure 2. Compressive strength of concrete with stock gradation FRAP. Error bars indicate one standard deviation. Conversion: 1 psi = 6.9 kPa.

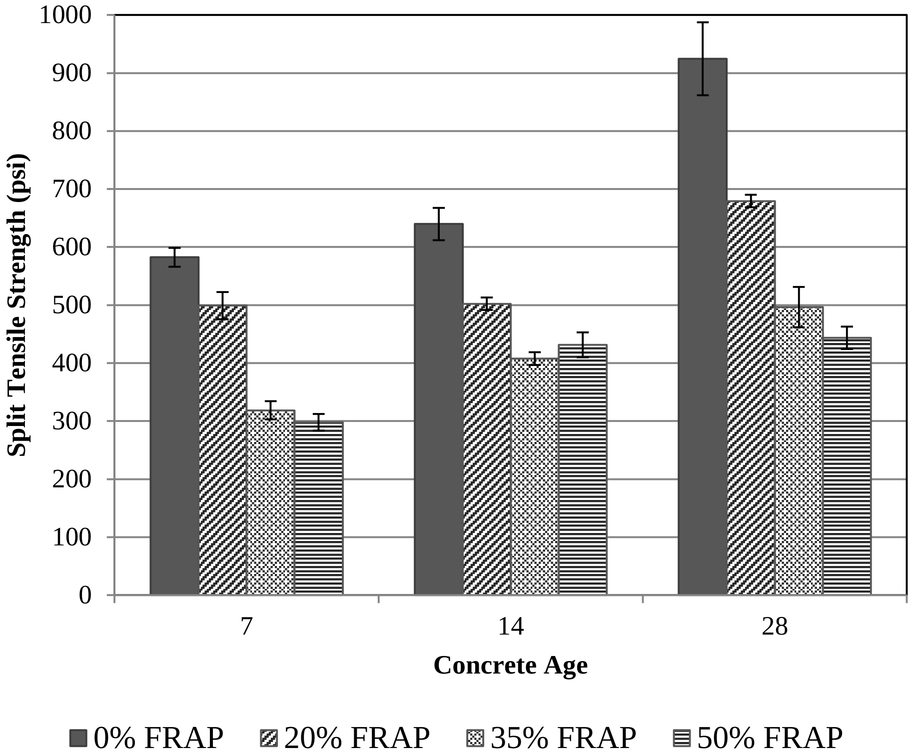

Figure 3. Split tensile strength of concrete with stock gradations FRAP. Error bars indicate one standard deviation. Conversion: 1 psi = 6.9 kPa.

The results for the gradation match compressive strength can be found in Figure 4. All four FRAP contents met the Illinois Department of Transportation requirement of 3,500 psi at 14 days. A comparison of the compressive strength results after the match gradation (Table 4) suggests that the gradation match may have an effect on the compressive strength. To determine if the concrete with FRAP match gradation is statistically significant, a t-test was conducted assuming a p-value of 0.05. The statistical significance results, shown in Table 5, reveal there was no significant difference trend in compressive strength between the concrete containing FRAP with stock gradation and match gradation. Due to the match gradation being more gap-graded in this study, this does not preclude that there could be a statistical difference in strength between a stock gradation and an optimized gradation (well-graded mix) for concrete containing FRAP.

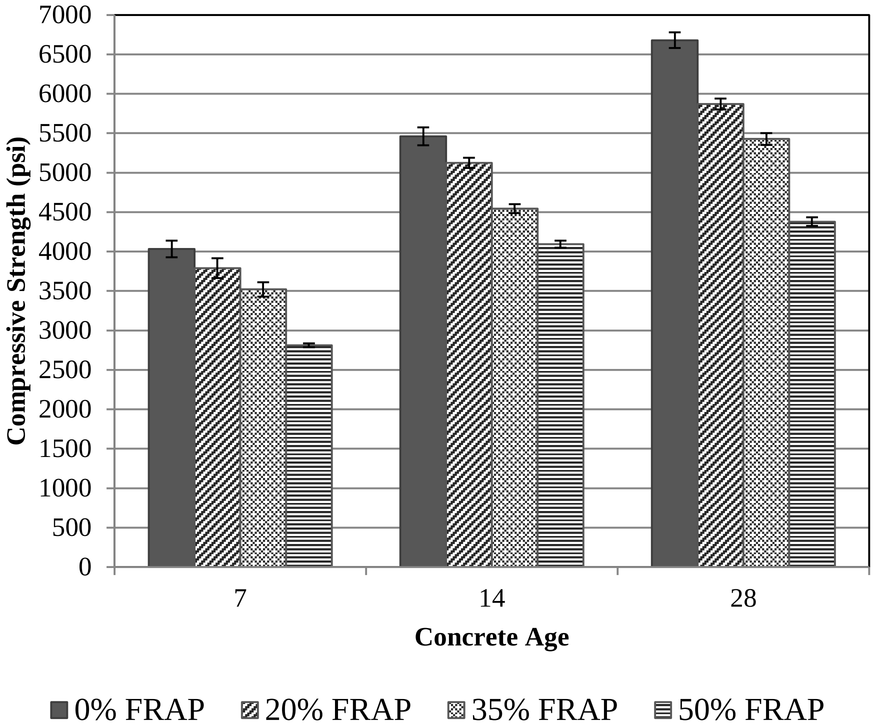

Figure 4. Concrete compressive strength for the FRAP gradation match study. Error bars indicate one standard deviation. Conversion: 1 psi = 6.9 kPa.

Table 4. Comparison of compressive strength results with stock and match gradation FRAPs.

Mix	Age (days)	Compressive Strength (psi)		Percent Difference
		Gradation Match	Stock Gradation	
0% FRAP	7	4,034	4,034	-
	14	5,460	5,460	-
	28	6,680	6,680	-
20% FRAP	7	3,789	3,341	13%
	14	5,125	4,623	11%
	28	5,872	5,391	9%
35% FRAP	7	3,520	3,427	3%
	14	4,543	3,871	17%
	28	5,427	4,745	14%
50% FRAP	7	2,812	2,970	-5%
	14	4,094	3,489	17%
	28	4,379	4,055	8%

1 psi = 6.9 kPa

Table 5. Statistical significance results comparing concrete containing stock to matched gradation FRAPs.

FRAP Content	Testing Age	t-value	p-value	Significance
20%	7	2.59	0.12	Not Statistically Significant
	14	4.79	0.04	Statistically Significant
	28	5.58	0.03	Statistically Significant
35%	7	0.76	0.53	Not Statistically Significant
	14	3.66	0.07	Not Statistically Significant
	28	5.78	0.03	Statistically Significant
50%	7	2.24	0.15	Not Statistically Significant
	14	6.99	0.02	Statistically Significant
	28	2.27	0.15	Not Statistically Significant

PAVEMENT SPECIFICATIONS AND PLANS FOR CONCRETE WITH FRAP

Tollway specifications for concrete mixes and pavements have been updated as a result of the laboratory research, trial mixes, and previous field projects. Concrete mixes will be produced using performance specifications instead of method specifications. Coarse FRAP processed off mainline Tollway roadways will be required in all bottom layer mixes (in two-lift concrete construction) to replace 20% to 50% of the virgin coarse aggregate. The use of RCA for any remaining coarse aggregate in bottom layer mixes will also be an option. All bottom layer mixes will be ternary blended concrete with 35% to 50% SCM replacement and optimized aggregate gradation to reduce the total paste content. The top layer of all concrete composite pavements will contain 100% virgin aggregate with either an Illinois Department of Transportation Class PV mix with a maximum of 35% SCM or a ternary virgin aggregate concrete mix designed with the Tollway's performance-based specification. Construction traffic will be allowed on the composite pavements when both lifts of the concrete have obtained a minimum third-point flexural strength of 475 psi and a compressive strength of 2,850 psi, at no less than 5 days age. Public traffic will be allowed on the pavements when strengths of 650 psi flexural (third-point) and 3,500 psi compressive are obtained at all locations.

The Tollway is designing the long-life composite pavements for gross vehicle weights of up to 120,000 pounds for both two-lift concrete and flexible over rigid sections. The concrete containing FRAP research has shown that the lower lift of composite concrete pavements is a prime location to use recycled aggregates (coarse FRAP and RCA) and ternary concrete mixtures. The following lists the Tollway's future plans for field and research projects that utilize concrete containing FRAP:

- A two-lift composite concrete pavement containing dirty FRAP will be placed on a six-lane, 0.7-mile expressway pavement on the Reagan Memorial Tollway (I-88) in 2012. The contractor will be using a ternary concrete mixture with 35% SCM and 20% dirty FRAP with an optimized aggregate gradation for the bottom lift and a standard virgin aggregate non-ternary mix for the top lift. Bid prices for the 11.5-inch jointed plain concrete composite pavement on I-88 were equivalent to prices recently received by the Tollway on other projects for standard single-lift jointed plain concrete pavement of similar thickness and quantity.
- Sixteen slabs were cast at the University of Illinois' Advanced Transportation and Research Engineering Laboratory facility in May 2012. The slabs were 6 by 6 feet and 6 inches thick and consisted of both full-depth and two-lift concrete slabs. Mixes for the monolithic and two-lift slabs included FRAP concrete, recycled concrete aggregate and FRAP concrete, virgin aggregate concrete, and fiber-reinforced FRAP concrete. Flexural load capacity tests will be completed in the summer of 2012 to determine the change in load level between virgin aggregate concrete slabs and slabs containing recycled aggregates in monolithic or two-lift construction.
- In the 2012 reconstruction of the Jane Addams Tollway (I-90) interchange with Illinois Route 47, seven ramps are being reconstructed as flexible over rigid composite pavements. The ternary concrete lower lift of the ramps will contain 45% SCM and 35% coarse FRAP with an optimized aggregate gradation. The top lift will be a polymerized, warm mix asphalt with over 35% virgin asphalt binder replacement.
- Recycled aggregates (FRAP and/or RCA) will be specified for all Tollway concrete pavement construction starting in 2013 when designed as a composite pavement for the reconstruction and widening of 62 miles of the Jane Addams Memorial Tollway (I-90). Recent off-site test strips for two-lift composite pavements proved that the proper modification of a belt placer/spreader box can eliminate the need for a slip form paver when placing the bottom lift. Simplified construction practices along with the use of higher recycled aggregate content in the lower lift mixes during I-90 reconstruction is expected to result in lower bid prices than what standard single-lift jointed plain concrete pavements would generate.

DESIGN OF LONG-LIFE SUSTAINABLE COMPOSITE CONCRETE PAVEMENTS FOR THE JANE ADDAMS MEMORIAL TOLLWAY (I-90)

Accurate characterization of the design inputs provides the foundation for a reliable long-life pavement design. In the laboratory part of this study, the properties of concrete with FRAP have been reviewed in this paper and elsewhere (Brand et al. 2012a, 2012b), which have shown that adequate strength and durability properties can be obtained with the use of FRAP. In designing long-life sustainable concrete pavements, the Tollway utilized the Mechanistic-Empirical Pavement Design Guide, as implemented in the DARWin-ME software, which allows for site-specific input values and data for climate, traffic, materials, and pavement structure that will achieve the long-life pavement objective (30- to 40-year initial service life). The following sections will summarize the inputs for the DARWin-ME structural design.

Climate Inputs

The climatic inputs for DARWin-ME are taken directly from weather station data. The Illinois Tollway's roadways are located near multiple high-quality airport weather stations with many years of historic climatic data. Specifically, the weather data were taken from O'Hare International Airport and the Chicago Rockford International Airport, depending on which airport was closest to the design section on I-90. This weather station data are used in the pavement design to compute the changes in stresses and material properties of the pavement structure during its anticipated service life.

Traffic Inputs

An important part of designing long-lasting concrete pavements is having traffic inputs that accurately reflect the loading that the pavements will experience in service. All designs for the Tollway mainline two-lift concrete pavements with FRAP were developed using modified truck traffic inputs that reflect the probable traffic that Tollway pavements will be carrying in the future. This requires evaluating truck weights as high as 120,000 pounds, lane distribution factors that are specific to Tollway truck usage, and load spectra that are matched to the current loads experienced on the Tollway. The development of heavy truck pavement design inputs requires a review of weigh-in-motion (WIM) data from various Illinois Tollway WIM locations and the default pavement design inputs in DARWin-ME.

Lane Distribution

The lane distribution factor for truck traffic can have a large impact on the pavement design, especially for long-life pavements. The default values for lane distribution factors were found to be considerably different on Illinois Tollway routes than the guidance provided in DARWin-ME. The differences are likely related to the geographic location of the Tollway and the mix of truck and commuter traffic on the Tollway's highways. Figure 5 shows the critical lane and corresponding lane distribution factor for the Illinois Tollway system. Not only is the percentage of trucks in the design lane notably higher for Tollway WIM data than the general national guidance, but the critical lane is also not the outside driving lane but is instead the second lane, with a 70% to 90% lane distribution factor. By using Tollway-specific lane distribution factors and the total truck count for a typical section of the Tollway, the actual number of trucks expected in the design lane is calculated to be over 55% higher than what would be assumed by the default pavement design traffic values for a typical interstate highway.

Vehicle Classification and Load Spectra of Current Truck Traffic

For the initial DARWin-ME pavement design, the vehicle class distribution selected for the Tollway system was the default category, TTC1, which consists primarily of single-trailer trucks. The load spectra (weights of axles for different truck and axle types) for the Illinois Tollway are different than the default load spectra distributions provided in DARWin-ME. These differences can influence the expected pavement performance, particularly in a long-life pavement design. The most frequent truck used on the Illinois Tollway system is a Class 9 truck (TTC1), which is a single steer axle, a tandem drive axle, and a tandem axle at the back of the trailer. Figure 6 shows a comparison of the typical tandem axle load distributions for the Class 9 truck from DARWin-ME and from the Tollway WIM data. The Tollway distribution clearly shows that there are a larger percentage of the trucks operating on the roadway that are at or near the legal load limit, but there are fewer overloaded trucks on the Tollway relative to the DARWin-ME default values.

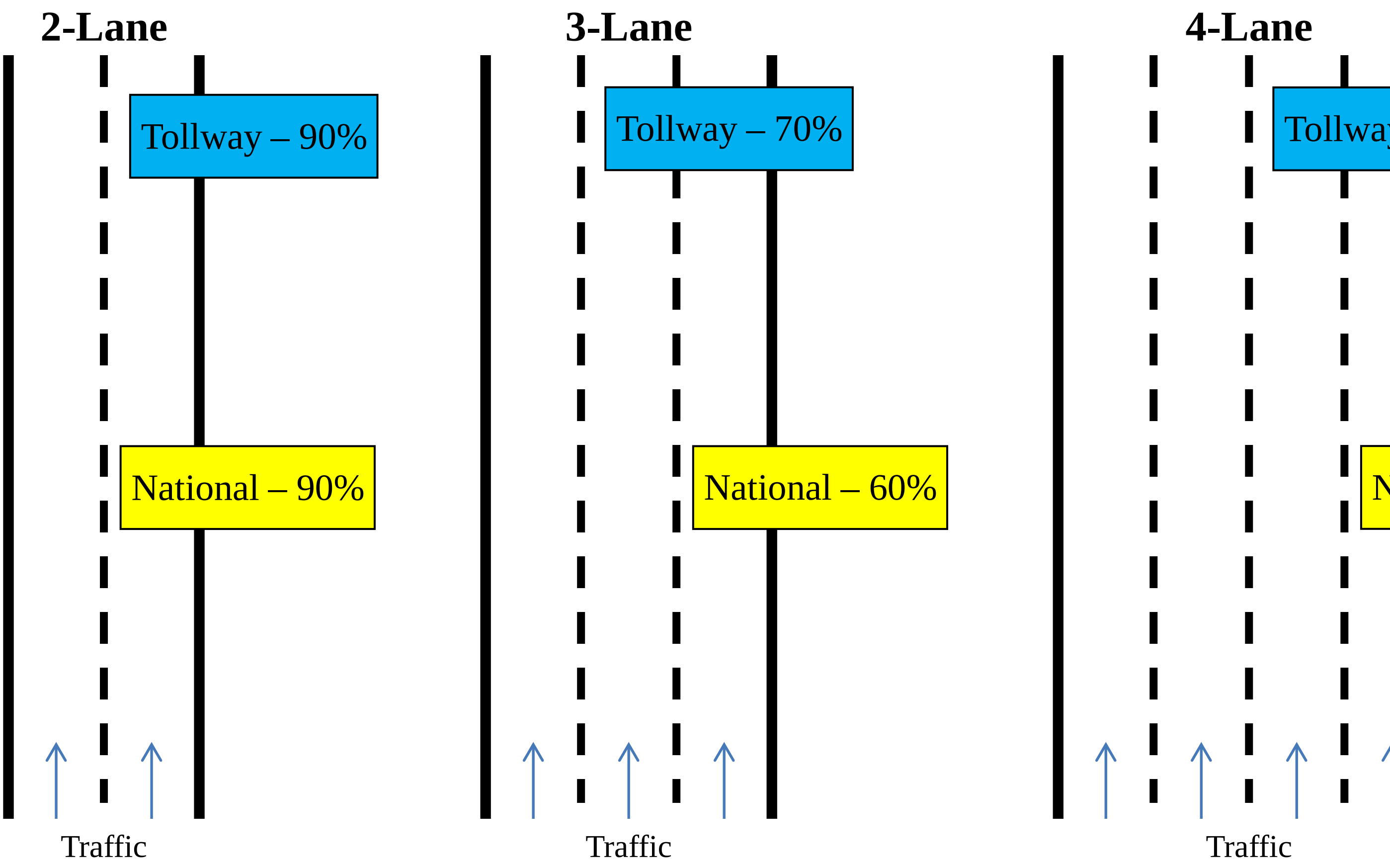

Figure 5. Critical lane and lane distribution factor based on Illinois Tollway WIM data and DARWin-ME defaults.

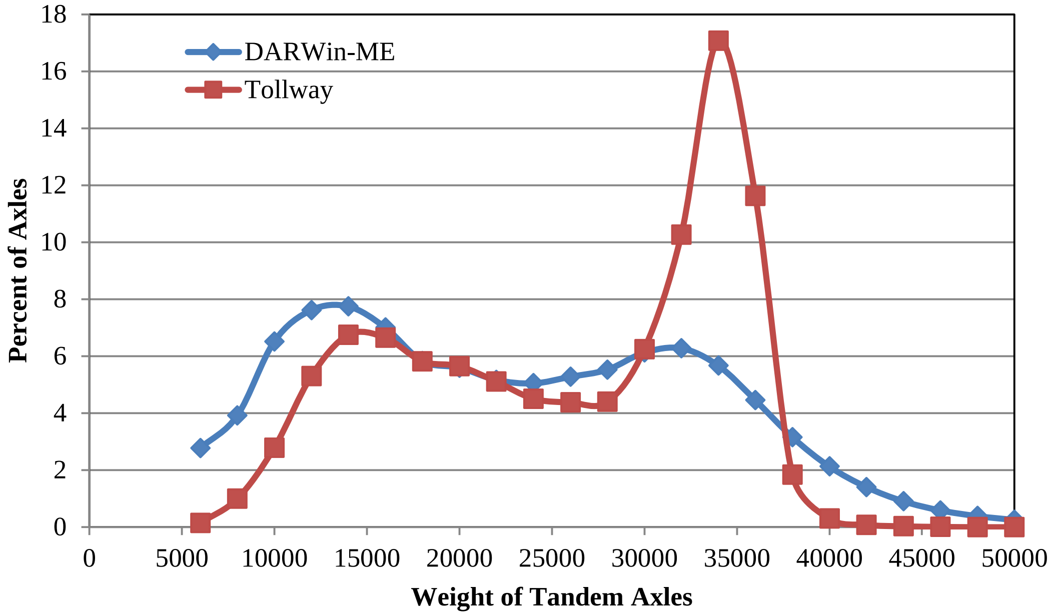

Figure 6. Example of axle load distributions for tandem axles (Class 9 truck) for the DARWin-ME default and Tollway WIM data.

Load Spectra of Expected Heavier Trucks

The truck classification and weight data were reviewed for nearby states (e.g., Iowa, Indiana, Michigan) where heavier truck loads are allowed. The primary source for these heavy truck traffic data was the Federal Highway Administration Long-Term Pavement Performance database (Release 25.0, January 2011). These data were used to understand the potential change to truck load spectra that would be expected with an increase in total truck weight to 120,000 pounds.

The analysis of Tollway and heavy truck data from other states resulted in modified axle load distributions for tandem and tridem axles for Class 10 (six-axle) trucks. Figure 7 and Figure 8 show the standard and modified axle load distributions for the tandem and tridem axles used in the design the Tollway's long-life pavements. These modified traffic inputs resulted in thicker pavement designs than would have normally been produced from DARWin-ME.

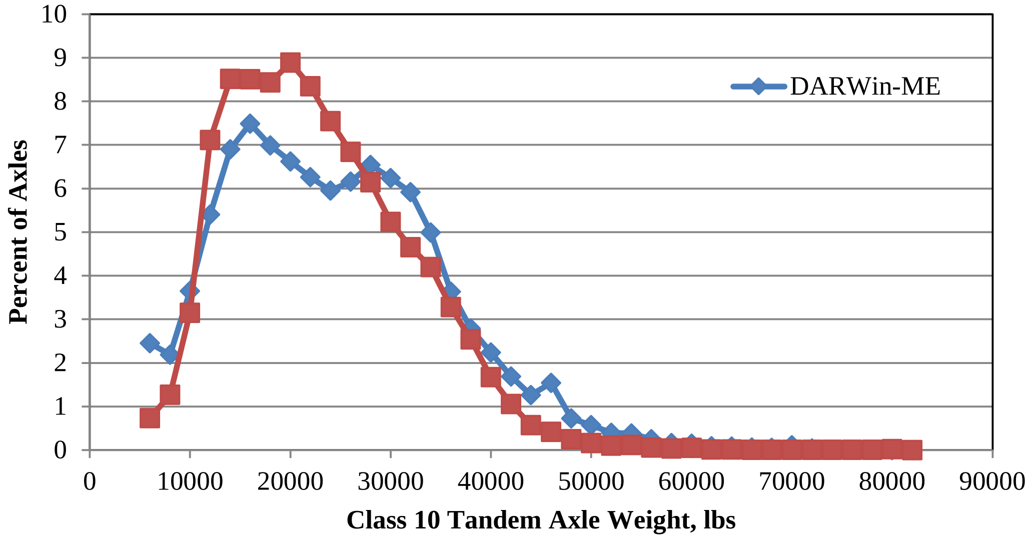

Figure 7. Example of axle load distributions for tandem axles from DARWin-ME and surrounding states.

Figure 8. Example of axle load distributions for tridem axles from DARWin-ME and surrounding states.

Two-Lift Concrete Pavement Design

In the two-lift portland cement concrete pavement design, where the bottom lift consists of FRAP concrete and the top lift consists of a virgin aggregate concrete, the primary objectives were to maximize the thickness of the FRAP concrete lift (while minimizing the overall pavement thickness) and still provide a suitable top-lift surface thickness to provide the necessary smoothness, friction, durability, and noise level. Other considerations for the two-lift pavement designs included the constructability of the two-lift pavement, the placement depth for the dowel bars at transverse joints, and the saw-cut depth.

Pavement Structure and Slab Thickness Design

The initial pavement structure was assumed to have a widened lane with an outside shoulder (asphalt shoulder), and the two-lift concrete pavement was cast on a 3-inch asphalt-stabilized base and a 12-inch aggregate subbase. While the addition of FRAP reduces the absolute strength of the concrete relative to a virgin aggregate concrete, the FRAP concrete has been shown to still be able to achieve an acceptable flexural strength of 650 psi. With concrete flexural strength as a primary factor in pavement thickness design, there is no anticipated change to the design strength and, therefore, no anticipated change to total pavement thickness when using the FRAP concrete as specified by the Tollway. Based on DARWin-ME designs, the slab thickness ranges from 12 to 14 inches depending on the projected traffic along I-90. The total composite concrete slab consisted of 9 to 11 inches of concrete containing FRAP on the bottom lift and 3 inches of virgin aggregate concrete as the top lift.

Dowel Placement

Dowel bar placement for the two-lift FRAP concrete pavement is based on the assumption that the top lift is bonded to the bottom lift, resulting in monolithic slab behavior. Based on this assumption, the 1.5-inch-diameter dowel bars are placed at the mid-depth of the combined two-lift slab thickness, as shown in Figure 9. The contraction joints are saw-cut all the way through the top lift (i.e., at least 3.5 inches) into the bottom lift to prevent any crack propagation along the two-lift concrete interface.

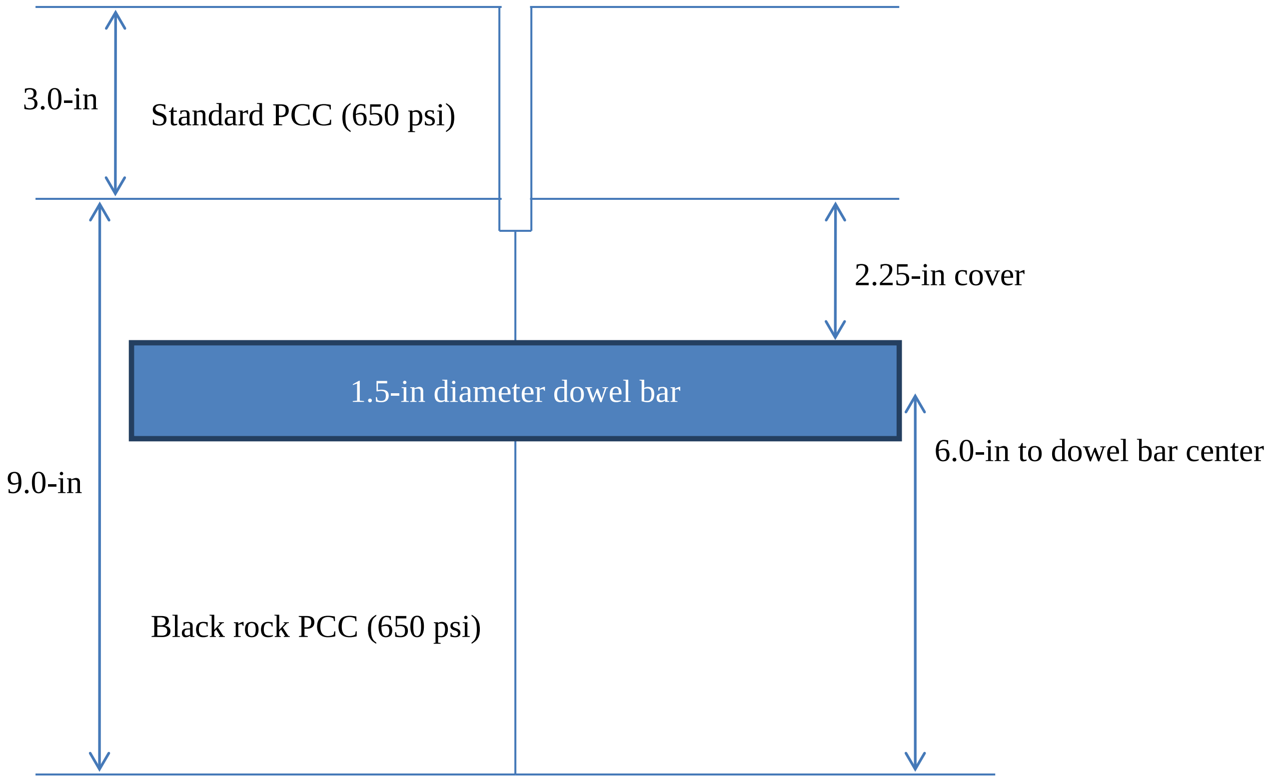

Figure 9. Dowel bar placement for 3-inch over 8-inch two-lift concrete pavement.
Conversions: 1 inch = 2.54 cm, 1 psi = 6.9 kPa.

Joint Spacing

In the jointed concrete pavement design process, the determination of slab length is based on finding an appropriate slab length without increasing slab thickness due to excessive mid-slab transverse cracking. The cost associated with shortening the slab length is notable, so a balance between the increased construction costs of shorter joints is weighed against the predicted performance benefits. In the case of the Tollway two-lift FRAP concrete pavement, a joint spacing of 15 feet was found to reasonably balance slab length and concrete thickness.

CONCLUSIONS

This study determined the amounts of high-quality coarse FRAP that can be utilized as a partial replacement of virgin coarse aggregate. Both clean FRAP (washed) and dirty FRAP (unwashed) can be utilized up to 50% replacement levels of the coarse aggregate and still meet the desired strength requirements. This study also shows that there is no discernible trend in the compressive strength when matching the coarse FRAP gradation to a typical virgin coarse aggregate gradation. In addition, a previously published report demonstrated that concrete with FRAP can have adequate durability properties.

Based on the results from the laboratory studies, the Tollway will be completing numerous trial sections utilizing FRAP concrete. The first test section on a highway ramp was completed in October 2010 with a 9-inch concrete with FRAP topped with a 3-inch hot-mix asphalt layer. Future test sections will include more ramps as flexible over rigid composite pavements as well as two-lift concrete sections, which will consist of a recycled material bottom lift (FRAP and/or recycled concrete aggregate) with a virgin aggregate concrete top lift. The Tollway's pavement management consultant, ARA, will monitor the performance of these test sections and all future composite pavements annually.

Future two-lift concrete sections have been designed using DARWin-ME. The design inputs for climate, traffic, materials, and pavement structure were assumed, measured, and evaluated for Tollway-specific inputs. The resultant pavement design include 12 to 14 inches of concrete split into a 9- to 11-inch bottom lift with FRAP concrete and 3-inch virgin concrete top lift and 15-foot dowelled joints.

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