Reclaimed Asphalt Pavement in Concrete Pavements:
Properties, Microstructure, and Design

Alexander S. Brand[1] and Jeffery R. Roesler

Abstract
Reclaimed asphalt pavement (RAP), when used as aggregate in concrete, is known to reduce the bulk concrete strength and modulus but not dramatically impact shrinkage, durability, or fracture properties, especially at lower replacement levels. This article presents an overview of RAP aggregates in concrete as it pertains to its effect on properties, microstructure, and pavement design. The mechanisms resulting in decreased strength and modulus for concrete containing RAP have been linked to: (1) the larger, more porous interfacial transition zone (ITZ) and (2) the dominance of an asphalt cohesion failure instead of an asphalt-cement adhesion failure. Despite these reductions in mechanical properties, multiple field studies have indicated that concrete with RAP can perform comparably to conventional concrete pavements, particularly when 10-15% RAP is used. The flexural capacity of concrete slabs with 22% RAP has shown similar behavior to virgin aggregate concrete given the similarities in fracture properties. Fatigue and accelerated pavement testing of roller-compacted concrete with high RAP contents (50-100%) have indicated a reduced fatigue life relative to plain concrete, requiring a slightly thicker design. Based on the literature, RAP aggregate replacement levels less than 25% can be used in concrete pavements without a significant change to the structural design.

Introduction

With the large volumes of reclaimed asphalt pavement (RAP) available because of pavement rehabilitation and the increased interest in sustainable design, the addition of RAP into concrete has undergone significant research recently, particularly in Illinois (Brand, Roesler, et al. 2012; Brand, Smith, et al. 2012; Gillen et al. 2012; Bentsen et al. 2013; Brand et al. 2014; Ferrebee et al. 2014; Brand and Roesler 2015, 2016a, 2016b, 2016c), Florida (Hossiney et al. 2008, 2010; Su et al. 2014), Tennessee (Huang et al. 2005, 2006), Montana (Berry et al. 2013, 2015a), and Texas (TTI 2015), as well as in France (Mathias et al. 2004; Bilodeau et al. 2011, 2012; Nguyen et al. 2012), Brazil (Sachet et al. 2011, 2013), and Greece (Katsakou and Kolias 2007). Despite a number of studies, dating as far back as 1970 (Patankar and Williams 1970),

[1] Department of Civil and Environmental Engineering , University of Illinois Urbana-Champaign, Urbana, Illinois, USA

there are few documents summarizing the overall effects of RAP on concrete properties and its impact on concrete pavement design. The objectives of this paper are to provide an abridged summary of previous studies on concrete containing RAP, discuss the microstructural mechanisms producing the bulk property changes, and provide concrete pavement design implications.

Literature Summary

A summary of the effect of RAP on concrete properties is presented in Table 1. The majority of studies have examined the mechanical properties (i.e., strength and modulus) with fewer studies characterizing its durability, shrinkage, and fracture properties. All studies have unanimously concluded that RAP addition will reduce the concrete strength (compression, split tension, flexure) and modulus (static or dynamic). As seen in Figure 1, the use of 50% coarse RAP can reduce the concrete flexural strength and elastic modulus by about 20% and 30%, respectively. Overall, most fracture properties of concrete with RAP have been found to not be statistically different from the same concrete with virgin aggregates (Brand et al. 2014; Ferrebee et al. 2014; Brand and Roesler 2015, 2016a), although the critical stress intensity factor (K_{Ic}) is typically less for concrete with RAP. Conclusions on other properties, such as concrete shrinkage and freeze/thaw durability, cannot be easily generalized, given the limited data in the literature.

Table 1. The Effect of RAP on Hardened Concrete Properties

Concrete Property	Effect on Property	References
Compressive strength	Decrease	Patankar and Williams 1970; Kolias 1996a; 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; Katsakou and Kolias 2007; Hossiney et al. 2008, 2010; Al-Oraimi et al. 2009; Okafor 2010; Bilodeau et al. 2011; Bly and Weiss 2012; Berry et al. 2013, 2015b; Modarres and Hosseini 2013; Capson and Sorensen 2013; Erdem and Blankson 2014; Ferrebee et al. 2014; Ibrahim et al. 2014; Su et al. 2014; Brand et al. 2014; Brand and Roesler 2015, 2016a, 2016c
Split tensile strength	Decrease	Patankar and Williams 1970; Kolias 1996a; Sommer and Bohrn 1998; Mathias et al. 2004; Huang et al. 2006, 2005; Katsakou and Kolias 2007; Hossiney et al. 2008, 2010; Bilodeau et al. 2011; Sachet et al. 2011, 2013; Capson and Sorensen 2013; Ibrahim et al. 2014; Su et al. 2014; Brand et al. 2014; Ferrebee et al. 2014; Brand and Roesler 2015, 2016a, 2016c
Flexural strength	Decrease	Patankar and Williams 1970; Sommer 1994; Kolias 1996a; Sommer and Bohrn 1998; Dumitru et al. 1999; Hassan et al. 2000; Katsakou and Kolias 2007; Hossiney et al. 2010, 2008; Al-Oraimi et al. 2009; Okafor 2010; Sachet et al. 2011, 2013; Bly and Weiss 2012; Berry et al. 2013; Modarres and Hosseini 2013; Brand et al. 2014; Erdem and Blankson 2014; Brand and Roesler 2015, 2016a
Direct tensile strength	Decrease	Patankar and Williams 1970; Katsakou and Kolias 2007
Superpave indirect tensile strength	Decrease	Su et al. 2014
Modulus of elasticity	Decrease	Patankar and Williams 1970; Kolias 1996a, 1996b; Delwar et al. 1997; Sommer and Bohrn 1998; Dumitru et al. 1999; Mathias et al. 2004; Huang et al. 2006; Katsakou and Kolias 2007; Hossiney et al. 2010, 2008; Al-Oraimi et al. 2009; Bilodeau et al. 2011; Berry et al. 2013; Su et al. 2014; Brand et al. 2014; Erdem and Blankson 2014; Brand and Roesler 2015, 2016a

Table 1 (continued). The Effect of RAP on Hardened Concrete Properties

Complex stiffness modulus	Decrease	Kolias 1996b; Bilodeau et al. 2011; Brand and Roesler 2015
Free shrinkage	Increase	Dumitru et al. 1999; Brand and Roesler 2016a
	Decrease	Hossiney et al. 2008
	Variable*	Hossiney et al. 2010; Ibrahim et al. 2014
	No Effect	Sommer 1994; Brand and Roesler 2015
Creep strains	Increase	Kolias 1996a
Coefficient of thermal expansion	Variable*	Hossiney et al. 2008, 2010
	Similar	Bentsen et al. 2013
Toughness and energy absorption	Increase	Huang et al. 2005, 2006; Modarres and Hosseini 2013; Su et al. 2014
Fatigue properties	Reduce	Mathias et al. 2004; Modarres and Hosseini 2013
	Similar	Modarres and Hosseini 2013†
Critical stress intensity factor, K_{Ic}	Statistically Similar	Brand et al. 2014; Ferrebee et al. 2014; Brand and Roesler 2015, 2016a
	Decrease	Sachet et al. 2011
Critical crack tip opening displacement $CTOD_c$	Statistically Similar	Brand et al. 2014; Ferrebee et al. 2014; Brand and Roesler 2015, 2016a
Strain energy release rate, G_{Ic}	Statistically Similar	Brand et al. 2014; Ferrebee et al. 2014; Brand and Roesler 2015, 2016a
Total fracture energy, G_F	Statistically Similar	Brand et al. 2014; Ferrebee et al. 2014; Brand and Roesler 2015, 2016a
Porosity	Increase	Hassan et al. 2000
	Similar	Modarres and Hosseini 2013; Su et al. 2013
Oxygen permeability	Increase	Hassan et al. 2000
Surface absorption	No Effect	Al-Oraimi et al. 2009
Salt scaling resistance	Decrease	Sommer 1994; Sommer and Bohrn 1998; Berry et al. 2013
Freeze/Thaw durability	Suitable	Berry et al. 2013; Brand and Roesler 2015
	Decrease‡	Brand and Roesler 2016a
Rapid chloride penetrability	Similar	Brand and Roesler 2015
Poisson Ratio	Variable*	Su et al. 2014

*Variable = no clear trend; †At stress ratios around 0.75; ‡With 50% coarse SFS RAP

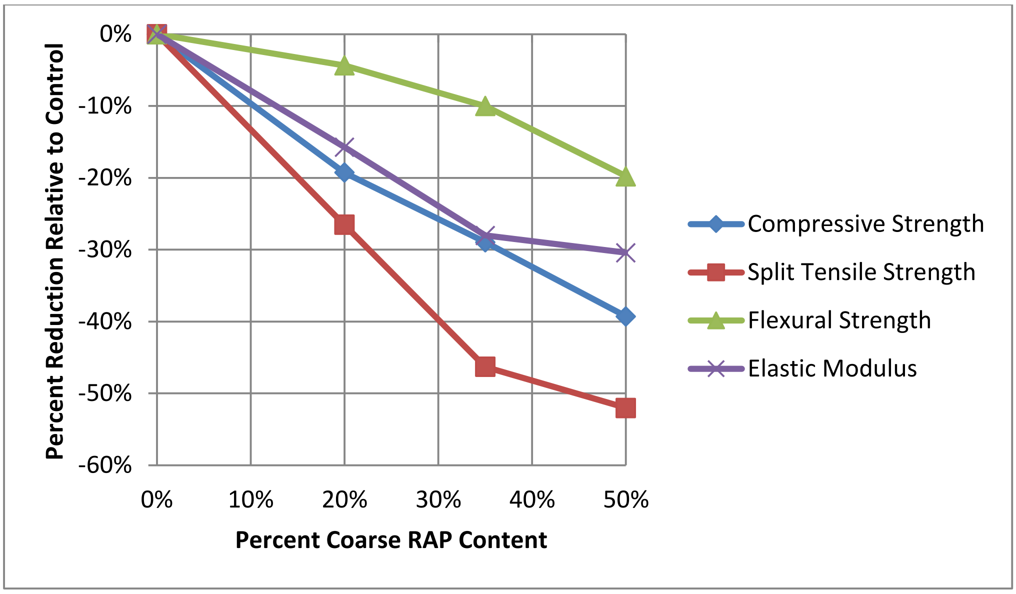


Figure 1. Percent reductions in 28-day compressive strength, 28-day split tensile strength, 14-day flexural strength, and 28-day static elastic modulus for concrete mixtures with coarse RAP relative to the control concrete (0% RAP) from Brand and Roesler (2015).

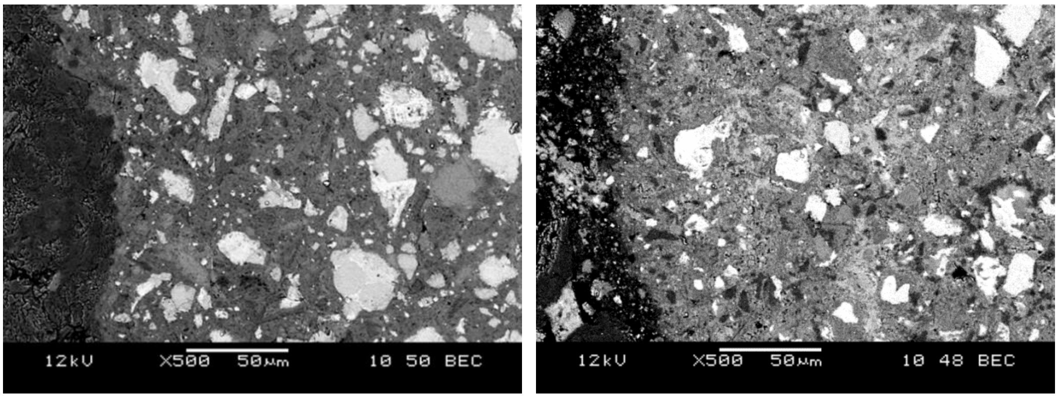
In general, the freeze/thaw durability of concrete with RAP has found to be suitable. After 300 freeze/thaw cycles, Brand and Roesler (2015) found durability factors of 101%, 102%, 90%, and 86% for concrete mixtures with 0%, 20%, 35%, and 50% coarse RAP, respectively. Similarly, after 300 freeze/thaw cycles, Berry et al. (2013) found durability factors of 94% and 98% for concrete mixtures labeled as "high RAP" (100% coarse RAP, 50% fine RAP) and "high strength" (50% coarse RAP, 25% fine RAP), respectively. However, in testing RAP that contained steel furnace slag (SFS) aggregates (SFS RAP), Brand and Roesler (2016a) found durability factors of 88% and 53% for concrete mixtures with 20% and 50% coarse SFS RAP, respectively. The mix with 50% coarse SFS RAP did not perform well possibly as a result of the asphalt content or asphalt type.

The results in Table 1 primarily concern the use of RAP sources that contain natural aggregates (i.e., dolomite, limestone, gravel). One study (Brand and Roesler 2016a) utilized RAP that contained SFS aggregates, which was taken from a surface course where SFS was added to improve the pavement frictional qualities and abrasion resistance. In terms of strength properties, the concrete with SFS RAP performed similarly to concrete with dolomite RAP. However, the elastic modulus was higher for concrete with SFS RAP relative to dolomite RAP, primarily because SFS is a stiffer, denser aggregate. For that study, concrete with SFS RAP experienced greater shrinkage and decreased freeze/thaw durability, possibly as a result of the asphalt content or asphalt type. Furthermore, SFS is inherently expansive as a result of the free calcium and magnesium oxides present in the slag, and SFS RAP may also be expansive (Senior et al. 1994; Deniz et al. 2010; Dayioglu et al. 2014; Brand and Roesler 2016a), depending on the SFS content and the extent of asphalt coating. Any stockpiles of RAP that may contain SFS should be screened for possible expansion potential with the free calcium oxide test (complexometric titration) and the rapid autoclave expansion test (Brand and Roesler 2016a). Overall, it is important to screen the RAP material for different source aggregates, as it may negatively impact the concrete properties.

An additional consideration regarding concrete with RAP is the effect of asphalt content and asphalt type on the performance of the concrete. While this topic has not been given explicit attention in the literature, the studies by Brand et al. (Brand, Roesler, et al. 2012; Brand, Smith, et al. 2012; Brand et al. 2014; Brand and Roesler 2016a) have examined concrete mixtures of similar composition with various RAP sources, which had different total asphalt contents (2.1-3.9%), different source asphalt types (PG 70-22, PG 76-22), different classifications of the asphalt extracted from the RAP (PG 76-22, PG 82-22, PG 88-22), and different aggregate types (dolomite, SFS). In general, the concrete with dolomite RAP (Brand and Roesler 2015) and concrete with SFS RAP (Brand and Roesler 2016a) demonstrated similar strengths, despite the differences in asphalt content and aggregate type. Additionally, Brand, Smith, et al. (2012) compared two RAP sources, one processed RAP with little fines content and one unprocessed “dirty” RAP with high fines content and found slightly different bulk concrete strengths. An additional study (Gillen et al. 2012) demonstrated that the bulk concrete strength can be slightly increased by changing the RAP gradation. Finally, the quantity of the RAP particle coated with asphalt was examined by Moaveni et al. (2016) using image processing techniques, the findings of which suggested that the total fracture energy of concrete with RAP correlated better with the percent asphalt coating on the aggregate (56-89%) compared to the total asphalt content of the RAP (2.1-3.9%).

Microstructural Properties

The first microstructural examination of concrete with RAP was conducted by Sachet et al. (2013). They used scanning electron microscopy (secondary electron imaging) to investigate fractured surfaces in a roller-compacted concrete with RAP. Qualitative analysis of the images suggested a weaker bond between the cement paste and RAP, possibly resulting in adhesion failures. Quantitative image analysis of the interfacial transition zone (ITZ) was conducted by Brand and Roesler (2016b). The ITZ of epoxy-impregnated sections of mortars with RAP, polished down to 0.25 μm, were imaged with compositional backscattered electron (BSE) microscopy (Figure 2). This study confirmed that the asphalt on the RAP fundamentally affects the ITZ behavior, particularly by increasing the size (width) of the ITZ and increasing the ITZ porosity while decreasing the amount of calcium silicate hydrate (C-S-H) in the ITZ, as seen in Figure 3 and Figure 4. The addition of silica fume, a pozzolan known to improve the ITZ properties (Mindess et al. 2003), did not greatly reduce the ITZ porosity in mortar with RAP (Figure 5), which confirms the finding in the literature that silica fume does not significantly improve the mechanical properties of concrete with coarse or fine RAP (Huang et al. 2006), as shown in Figure 6.



(a) (b)

Figure 2. Compositional BSE micrographs of the ITZ of mortar with (a) dolomite (aggregate on the left) and (b) RAP (asphalt mastic on the left). In BSE micrographs, light atomic elements or compounds appear dark, such as the black carbon-based epoxy-filled pores and black hydrocarbon asphalt, while heavy atomic elements appear bright, such as the iron-containing unhydrated cement. Calcium hydroxide appears light grey while C-S-H appears dark grey. Source: Brand and Roesler (2016b)

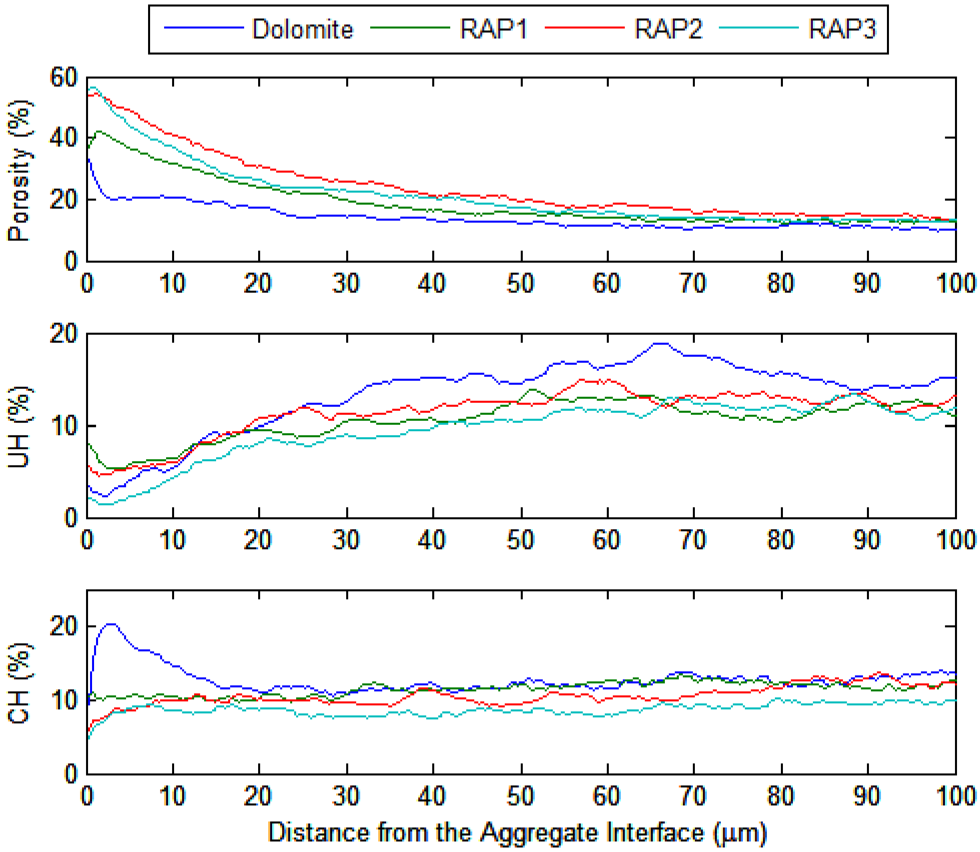


Figure 3. The distribution of detectable porosity, unhydrated (UH) cement, and calcium hydroxide (CH) for 28-day mortars with dolomite and three different RAP sources (RAP1, RAP2, RAP3). Each line represents the amount averaged over at least 50 images. Source: Brand and Roesler (2016b)

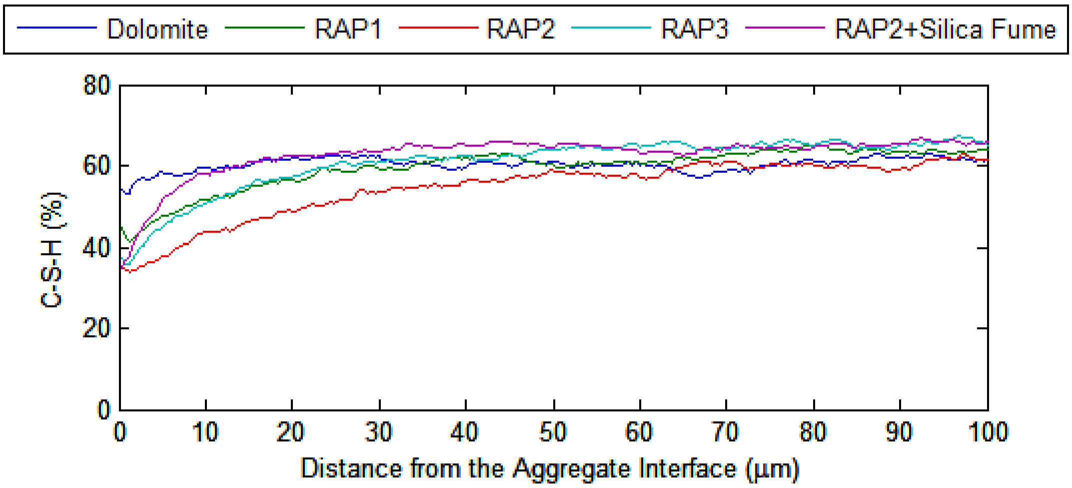


Figure 4. Estimated C-S-H content for 28-day mortars with dolomite, three different RAP sources (RAP1, RAP2, RAP3), and RAP with silica fume. Each line represents the amount averaged over at least 50 images. Source: Brand and Roesler (2016b)

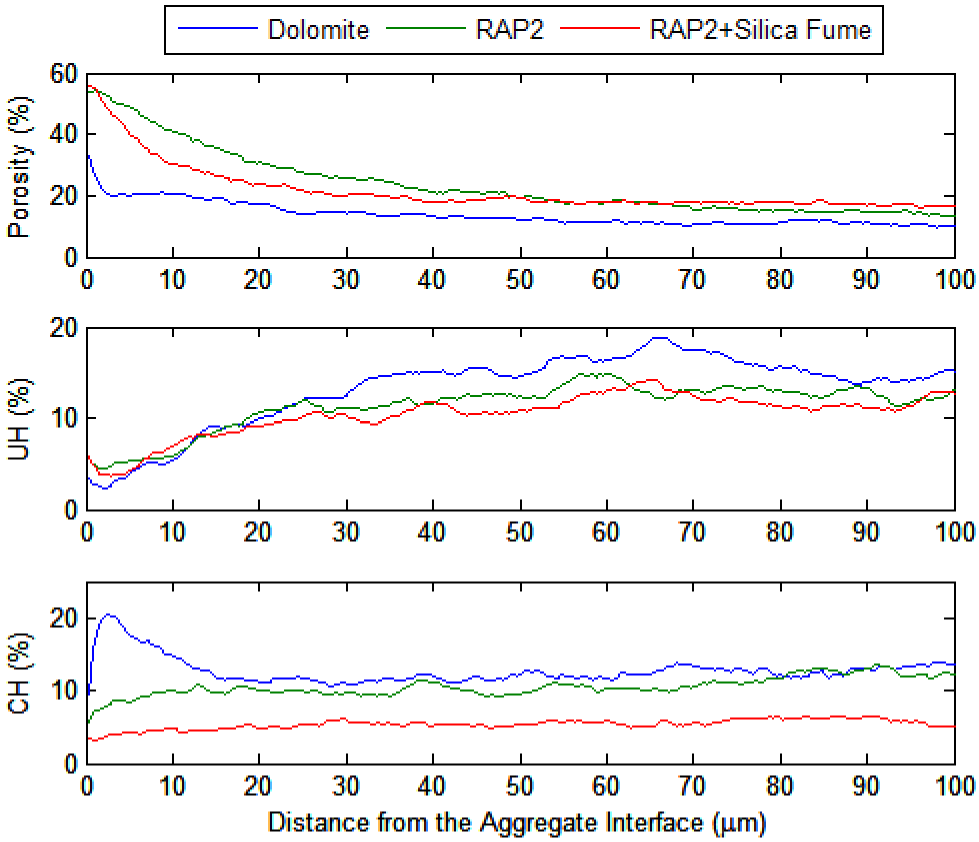


Figure 5. Comparison of average detectable porosity, UH, and CH at 28 days for mortar with dolomite, RAP, and RAP with silica fume. Each line represents the amount averaged over at least 50 images. Source: Brand and Roesler (2016b)

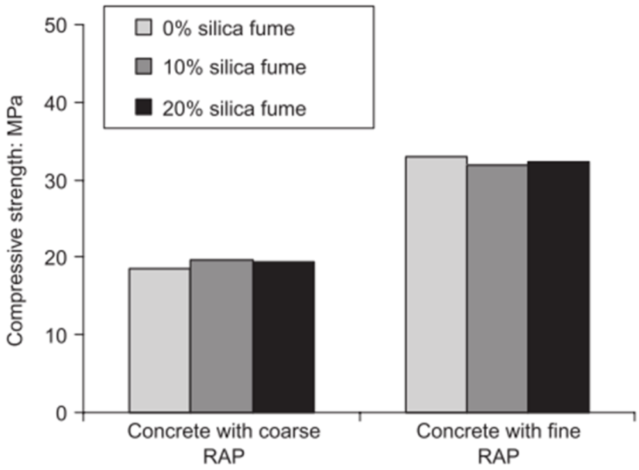


Figure 6. The effect of silica fume on the compressive strength of concrete with coarse or fine RAP. Source: Huang et al. (2006)

Based on these ITZ microstructural findings, it was concluded that the larger, more porous ITZ was the source of the reduction in elastic modulus. This behavior was theoretically confirmed using composite multiphase elastic models to predict the elastic modulus of concrete with different RAP contents (Brand 2015). Additionally, the more porous (and weaker) ITZ allows for easier crack initiation and propagation, leading to lower bulk strength. Finally, the greater amount of calcium hydroxide immediately at the paste interface with dolomite aggregate could be a source of improved bonding, such as through the formation of a calcium carbonate hydrate phase (Monteiro and Mehta 1986), which is not seen in the RAP ITZ.

Additional microstructural investigations explored the chemical bonding between cement paste and asphalt using surface free energy measurements and analyses (Brand and Roesler 2016c). Using the sessile drop method and van Oss-Chaudhury-Good theory (van Oss et al. 1988), the work of adhesion between asphalt and cement was found to be greater than the work of cohesion of the asphalt (Brand and Roesler 2016c), which means that the failure mode in cementitious composites with RAP will preferentially occur through the asphalt layer (i.e., asphalt cohesion failure) rather than through the asphalt-cement interface (i.e., asphalt-cement adhesion failure) or the cement (i.e., ITZ cohesion failure). This predominant asphalt cohesion failure mode was validated through additional interfacial bond tests with three point bend specimens (Brand and Roesler 2016c) and was different than the original mechanism proposed by Sachet et al. (2013) of asphalt-cement adhesion failure.

Based on the previous microstructural studies (Brand and Roesler 2016b, 2016c), the inclusion of RAP in concrete reduces the bulk concrete strength and modulus for two main reasons:

(1) *The larger, more porous ITZ*. The more porous ITZ allows for easier crack initiation and propagation, thus reducing the concrete bulk strength. Likewise, a more porous ITZ results in a lower bulk modulus of the concrete.
(2) *The cohesive failure of asphalt preferentially occurs instead of an adhesive failure of the cement-asphalt interface or cohesive failure of the ITZ*. Overall, the asphalt

cohesion failure is the limiting factor in the bulk strength, as the cement matrix will continue to gain strength with time through hydration but failure will still occur cohesively within the asphalt film.

Concrete Pavement Design Considerations

Given some of the potentially detrimental effects that higher RAP contents have on the concrete properties (see Table 1), concrete with RAP is well-suited for use as the bottom lift in two-lift pavement applications, which is a concept that has been applied in the field in Kansas (Wojakowski 1998), Iowa (Bergren and Britson 1977), and Austria (Sommer 1994) and most recently for the Illinois Tollway (Gillen et al. 2012; Bentsen et al. 2013). Additional field studies have also demonstrated the viability of RAP in roller-compacted concrete (RCC) applications (Bilodeau et al. 2011, 2012; Nguyen et al. 2012; Modarres and Hosseini 2013; Ferrebee et al. 2014). Despite these field sections, few studies have discussed how the use of RAP may affect concrete pavement design.

Flexural Capacity of Large-Scale Concrete Slabs. Since studies had shown concrete with RAP to experience strength and modulus reductions while retaining suitable fracture properties, Brand et al. (2014) evaluated the flexural load capacity of large-scale concrete slabs. The slabs were nominally 6 ft. by 6 ft. (1.8 m by 1.8 m) and 6 in. (150 mm) thick. The two-lift construction nominally consisted of a 4 in. (100 mm) bottom lift with 45% coarse RAP (22% RAP by total aggregate weight) and a 2 in. (50 mm) top lift with virgin aggregates. The average flexural capacity of two replicate slabs is shown in Table 2, indicating that the maximum (computed) stress at failure is similar to or greater for concrete with RAP compared to virgin aggregate concrete. Likewise, the ratio of the maximum stress at failure to the flexural strength from a laboratory-sized beam (150 mm by 150 mm by 510 mm) indicated that pavement thickness design based on the beam flexural strength significantly underpredicted the slab flexural capacity for concrete containing RAP relative to virgin aggregate concrete.

A conventional rigid pavement design concludes that concrete with RAP requires a thicker slab, based on the reduction in the beam flexural strength. However, given the similar measured flexural load capacities, a thicker slab may not be necessary, thus allowing concrete with RAP to be an economically viable solution. One method to maintain similar slab thickness within current design frameworks is to assume that the RAP does not affect the design flexural strength, given that the concrete with RAP has similar fracture properties to the typical virgin concrete mixture. For example, the Illinois Tollway assumed a design flexural strength of 650 psi (4.5 MPa) in their two-lift concrete pavement design (Gillen et al. 2012). Concrete with up to 35% coarse RAP has been shown to meet this 650 psi (4.5 MPa) requirement at 14 days (Brand and Roesler 2015) and concrete with 50% coarse RAP can exceed 650 psi (4.5 MPa) at 28 days (Brand and Roesler 2016a), despite neither of the mixes giving the equivalent to strength to virgin aggregate concrete.

Table 2. Slab Testing Results for Concrete with RAP (Brand et al. 2014)

Slab Type	Slab Description	Average Computed Maximum Stress at Failure (psi)	Average Slab Tensile Stress to Beam Flexural Strength Ratio
Full-Depth	Virgin Aggregate	1,186	1.51
Full-Depth	22% RAP	1,346	2.31
Two-Lift	Virgin over 22% RAP	1,400	2.40
Two-Lift	Virgin over 22% RAP with structural fibers	1,213	2.69

Fatigue Resistance of Concrete with RAP. While the structural design of rigid pavements is primarily based on the concrete fatigue life, there are only a few studies that have considered the fatigue resistance of concrete with RAP (Mathias et al. 2004; Modarres and Hosseini 2013). Modarres and Hosseini (2013) examined the impact of coarse and fine RAP on the fatigue life of roller-compacted concrete (RCC) with 285 kg/m^3 (480 lb/yd^3) of cement. The fatigue data, shown in Figure 7, suggest that similar fatigue lives (N_f) can be obtained for RCC mixtures with and without RAP at stress ratios (SR) greater than 0.70. Figure 7 also indicates that RCC mixtures with either 100% coarse or 100% fine RAP will have similar fatigue lives at any stress ratio. Finally, RCC mixtures with 100% coarse and 100% fine RAP had the shortest fatigue life at stress ratios less than 0.70. Comparing the RCC fatigue relationships from Modarres and Hosseini (2013) to the "zero maintenance" fatigue relationship for plain concrete (Darter 1977; Darter and Barenberg 1977) (see Figure 7 and Table 3), the fatigue resistance of plain concrete is greater than published curves for RCC with and without RAP. The fatigue life discrepancies between the plain concrete and RCC materials can be likely linked to the different cement contents employed and compaction methods utilized.

However, knowing that the fracture properties are critical to concrete slab flexural capacity, particularly when recycled aggregates are used (Brand et al. 2014), one study (Ferrebee et al. 2014) examined the fracture properties of RCC with 16% RAP (by total aggregate) and found that the critical stress intensity factor and total fracture energy can be greater than conventional concrete, suggesting that RCC with RAP may experience similar to greater flexural slab capacities than virgin aggregate concrete of similar thickness.

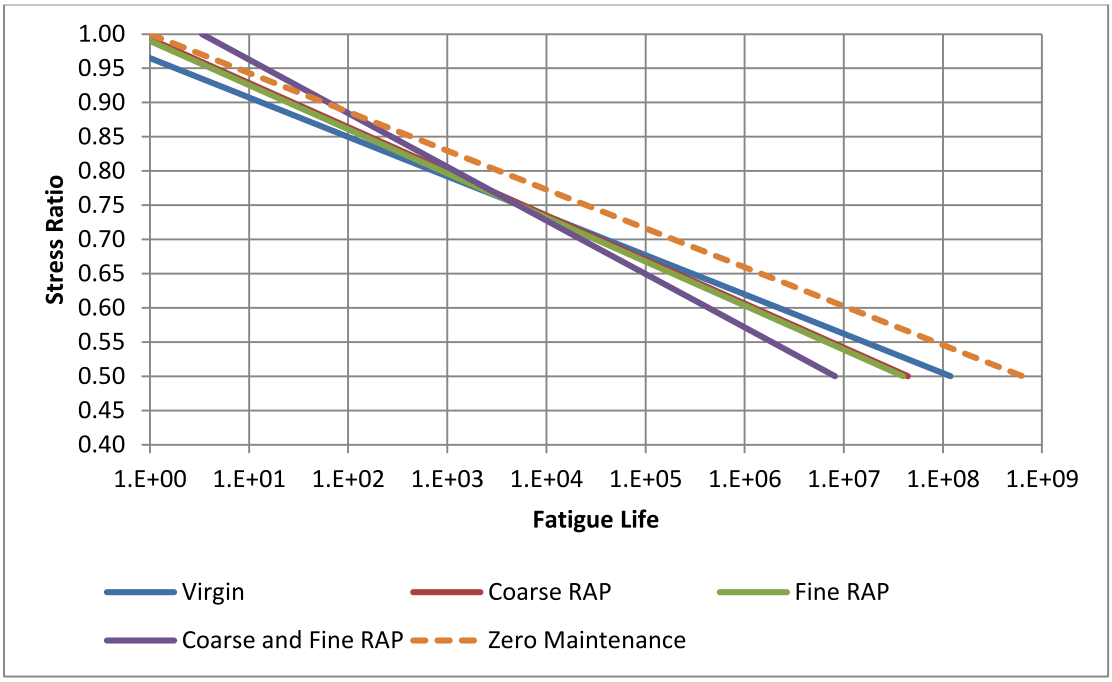


Figure 7. Fatigue data indicating the effect of using virgin aggregates (control), 100% coarse RAP, 100% fine RAP, or 100% coarse RAP and 100% fine RAP in RCC (solid lines) relative to the zero maintenance fatigue curve for plain concrete (dashed line). Adapted from Modarres and Hosseini (2013), Darter (1977), and Darter and Barenberg (1977).

Table 3. Fatigue Relationships for RCC With and Without RAP and Plain Concrete

Description	Fatigue Relationship	Reference
RCC with virgin aggregates	$\ln N_f = \dfrac{0.965 - SR}{0.025}$	Modarres and Hosseini (2013)
RCC with 100% coarse RAP	$\ln N_f = \dfrac{0.993 - SR}{0.028}$	
RCC with 100% fine RAP	$\ln N_f = \dfrac{0.990 - SR}{0.028}$	
RCC with 100% coarse and fine RAP	$\ln N_f = \dfrac{1.041 - SR}{0.034}$	
Plain concrete fatigue equation (Zero Maintenance)	$\log N_f = 17.61 - 17.61\,SR$	Darter (1977); Darter and Barenberg (1977)

Mathias et al. (2004) also conducted fatigue tests on concrete with RAP contents varying from 0 to 90% replacement of total aggregate, specifically for concrete for pavement surface courses (cement content of 330 kg/m^3 or 560 lb/yd^3) and lean concrete for base courses (cement content of 220 kg/m^3 or 370 lb/yd^3). For both mixture types, the stress ratio to produce failure after one million cycles decreased with increasing RAP content. The stress ratio to produce failure after one million cycles was approximately 0.5, 0.46, and 0.42 for the surface course concrete with 0%, 50%, and 90% RAP, respectively, and approximately 0.58 and 0.52 for the base course lean concrete with 0% and 90% RAP, respectively. The Mathias et al. (2004) fatigue data reported was for total aggregate replacement with RAP of 50%

and 90%, which are much greater RAP contents than monotonic slab tests by Brand et al. (2014) but similar to the RCC fatigue tests by Modarres and Hosseini (2013) study. Based on their fatigue data, Mathias et al. (2004) reported design CRCP thicknesses of 15 cm (5.9 in.), 17 cm (6.7 in.), and 20 cm (7.9 in.) over a 9 cm (3.5 in.) asphalt stabilized base when the CRCP concrete contained 0%, 50%, and 90% RAP by weight of total aggregate, respectively.

The available fatigue data in the literature suggest a reduced fatigue life for concrete with higher RAP contents (>50% total aggregate replacement). However, there is insufficient data available for concrete with lower RAP replacement levels (<30%), although the literature suggests similar slab capacity given that the concrete with RAP has similar fracture properties to virgin aggregate concrete.

Field Performance of Concrete with RAP. A number of field test sections and accelerated pavement tests have been conducted on concrete with RAP. The first concrete with RAP section reported in the literature was in Iowa in the 1970s, where an existing concrete pavement with an asphalt overlay was crushed and reused as aggregate (i.e., containing both recycled concrete aggregate and RAP) in the new concrete pavement, specifically in the bottom course of a two-lift concrete pavement (Bergren and Britson 1977). A similar concept was also applied in Austria in the 1990s where the bottom lift contained recycled concrete with about 10% RAP (Sommer 1994). About 200 miles (320 km) of the A1 freeway in Austria was constructed with this two-lift design and was reported to be performing well after 20 years (Rao et al. 2013). A field demonstration project of concrete with RAP was also recently conducted in Montana (Berry et al. 2015a), which indicated suitable performance over two years.

Kansas was the first state to field test a concrete pavement with only RAP and virgin aggregates. This was part of a High Performance Concrete Pavement study consisting of 12 different sections, one of which was a two-lift concrete pavement with 15% RAP in the bottom lift (Wojakowski 1998). The sections were built in 1997 and have been surveyed periodically, as shown in Table 4, comparing the control (virgin aggregate) full-depth pavement section to the two-lift pavement sections. Overall, the two-lift pavement section with RAP aggregates is currently performing similarly to the other test sections. Additionally, testing of the joint load transfer efficiency by falling weight deflectometer (FWD) has indicated that the two-lift concrete with RAP can perform similarly to a full-depth conventional concrete pavement (Figure 8).

Accelerated pavement testing (APT) has recently been conducted in France on fiber-reinforced RCC (FRCC) with RAP aggregates (Bilodeau et al. 2012; Nguyen et al. 2012). A number of FRCC test sections were constructed that had mixtures with and without RAP, at various thicknesses (12 to 15 cm; 4.7-5.9 in.) and loaded over nine months with over 2 million passes of a 65 kN (14.6 kip) dual wheel load. The FRCC RAP mixture contained 70% RAP, 18% sand, and 12% cementitious binder. Based on the APT and laboratory testing results, the authors developed a thickness design for FRCC when used as a base material, and it was found that FRCC with RAP needed to be 1-2 cm (0.4-0.8 in.) thicker than FRCC with hard limestone aggregates. Experimental field test sections of FRCC with RAP have also been constructed in France (Bilodeau et al. 2011, 2012); these test sections included FRCC with 0%, 36%, and 70% RAP by total dry mixture volume.

Table 4. Average Joint Faulting and Joint Spalling for the Kansas High Performance Concrete Pavement 1998-2010

Test Section No.	Section Description	Average Joint Faulting (mm)*				
		1998	1999	2002	2003	2010
1	Control (Full depth virgin aggregate concrete)	0.02	0.02	0.02	0.25	0.15
9	Two-lift with RAP	0.05	0.13	0.05	0.00	0.22
11	Two-lift with igneous rock	0.02	0.02	0.07	0.00	0.18
12	Two-lift with lower w/c	0.13	0.17	0.12	0.08	0.08
Test Section No.	Section Description	Average Joint Spalling (mm/joint)*				
		1998	1999	2002	2003	2010
1	Control (Full depth virgin aggregate concrete)	4.9	15.24	65.2	41.5	67
9	Two-lift with RAP	n/a	n/a	17.8	11.0	83
11	Two-lift with igneous rock	n/a	n/a	27.1	21.2	74
12	Two-lift with lower w/c	n/a	n/a	12.7	24.6	75

*Source: FHWA 2006; McLeod 2010

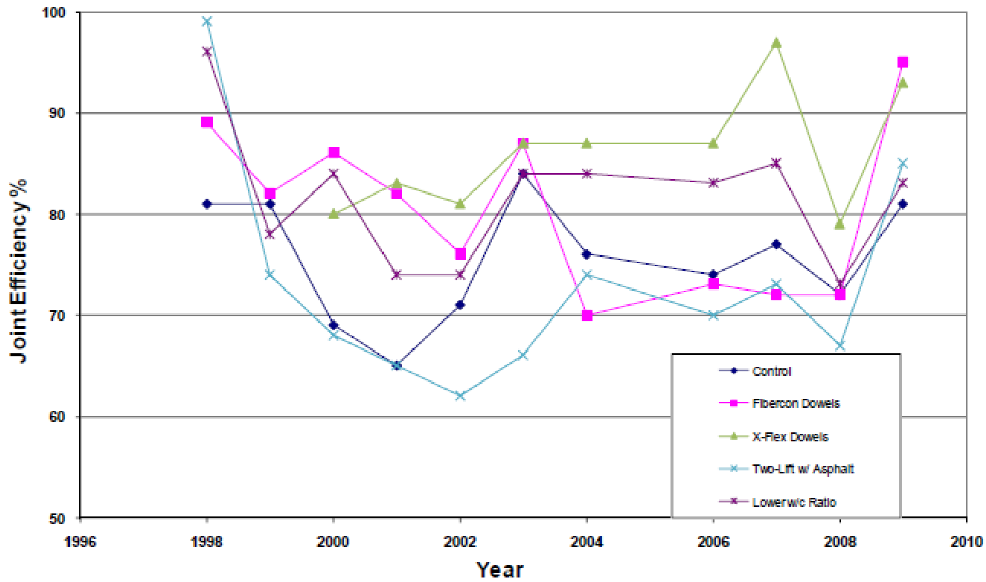


Figure 8. Joint efficiency results based on FWD testing of the Kansas High Performance Concrete Pavement 1998-2009. Source: Kansas Department of Transportation (McLeod 2010).

While there is limited field performance data available, the existing data suggests that field sections of concrete (or RCC) with lower RAP contents (<15%) may perform suitably if not comparably to conventional (virgin aggregate) concrete pavements. The Kansas and Austrian two-lift sections, which contained 10-15% RAP, have exhibited suitable performance, which agrees with the large-scale slab test results by Brand et al. (2014). The French APT results for FRCC with high RAP contents (70%) indicated performance slightly worse than FRCC with limestone, thus requiring a slightly thicker base design (Nguyen et al. 2012), which agrees with the fatigue results of RCC with RAP by Modarres and Hosseini (2013).

Conclusions

The use of reclaimed asphalt pavement (RAP) has seen a rise in interest as a partial to full replacement of aggregate in concrete and other cementitious composites. The literature reveals that use of RAP as an aggregate will cause reductions in the bulk concrete strength and modulus. While there is insufficient data to draw definitive conclusions, some of the literature suggests that RAP aggregates may not affect the bulk concrete shrinkage, coefficient of thermal expansion, energy absorption, or fracture properties.

Through measurement of the properties of the interfacial transition zone (ITZ) and the bonding between RAP (i.e., asphalt) and cement paste, the following two mechanisms produce the observed reductions in bulk concrete strength and modulus for RAP in concrete: 1) RAP aggregates produce a larger, more porous ITZ relative to virgin aggregates, and 2) surface free energy measurements and interfacial bond testing have shown that asphalt cohesion failures are more likely than an asphalt-cement adhesion failures. Because of this asphalt cohesion failure dominance, there has been limited success in significantly improving the bulk strength and modulus of concrete containing RAP.

Based on the reduction in concrete strength with RAP aggregates, conventional pavement designs would require a thicker pavement. However, the concrete fracture properties have been found not to be significantly affected by the addition of lower replacement levels of RAP, with one study finding that the flexural capacity of large-scale concrete slabs containing 22% RAP was similar if not greater than concrete slabs with virgin aggregates. With this in mind, one design implication is to assume a similar design flexural strength with similar mixture proportions and virgin aggregates. Field studies of concrete with low RAP replacement levels (10-15%), particularly the two-lift concrete sections in Kansas and Austria, have indicated suitable long-term performance. Fatigue and accelerated pavement testing of roller-compacted concrete with high RAP replacement contents (50-100%) indicate a reduced fatigue life, thus requiring a slightly thicker base course design. Ultimately, the literature supports that concrete with RAP aggregates can be successfully utilized in pavement applications, particularly in a two-lift or roller-compacted concrete construction, and significant adjustments to the design procedure may not be necessary when low RAP contents (<25%) are used.

References

Al-Oraimi, S., Hassan, H.F., and Hago, A., 2009. Recycling of reclaimed asphalt pavement in portland cement concrete. *Journal of Engineering Research*, 6 (1), 37–45.

Bentsen, R.A., Vavrik, W.R., Roesler, J.R., and Gillen, S.L., 2013. Ternary blend concrete with reclaimed asphalt pavement as an aggregate in two-lift concrete pavement. *In*: *Proceedings of the 2013 International Concrete Sustainability Conference*. San Francisco, California: National Ready Mixed Concrete Association.

Bergren, J. V. and Britson, R.A., 1977. *Portland Cement Concrete Utilizing Recycled Pavement.* Report MLR-7703, Ames: Iowa Department of Transportation.

Berry, M., Stephens, J., Bermel, B.N., Hagel, A., and Schroeder, D., 2013. *Feasibility of reclaimed asphalt pavement as aggregate in portland cement concrete pavement*. Report No. FHWA/MT-13-009/8207, Montana State University, Bozeman.

Berry, M., Dalton, K., and Murray, F., 2015a. *Feasibility of reclaimed asphalt pavement as aggregate in portland cement concrete pavement, phase II: field demonstration.* Report No. FHWA/MT-15-002/8207-002, Montana State University, Bozeman.

Berry, M., Kappes, B., and Kappes, L., 2015b. Optimization of concrete mixtures containing reclaimed asphalt pavement. *ACI Materials Journal*, 112 (6), 723–733.

Bilodeau, K., Sauréat, C., Benedetto, H. Di, Olard, F., and Bonneau, D., 2011. Laboratory and in situ investidgations of steel fiber reinforced compacted concrete containing reclaimed asphalt pavement. *In*: *Compendium of Papers, 90th Annual Meeting of the Transportation Research Board*. Washington, D.C.

Bilodeau, K., Sauzéat, C., Benedetto, H. Di, and Olard, F., 2012. Roller compacted concrete for road base layer with RAP and steel fibers : viscous properties and description of experimental sites. *In*: *10th International Conference on Concrete Pavements*. Québec City, Canada, 435–448.

Bly, P.G. and Weiss Jr., C.A., 2012. Performance of concrete pavement mixtures with marginal aggregates: laboratory investigation. *In*: *Proceedings of the 10th International Conference on Concrete Pavements*. Québec City, Canada, 801–827.

Brand, A.S., 2015. Interfacial transition zone composition and bonding in cementitious systems with asphalt-coated particles. PhD Dissertation, University of Illinois, Urbana, Illinois.

Brand, A.S., Amirkhanian, A.N., and Roesler, J.R., 2014. Flexural capacity of full-depth and two-lift concrete slabs with recycled aggregates. *Transportation Research Record*, 2456, 64–72.

Brand, A.S. and Roesler, J.R., 2015. Ternary concrete with fractionated reclaimed asphalt pavement. *ACI Materials Journal*, 112 (1), 155–164.

Brand, A.S. and Roesler, J.R., 2016a. Expansive and concrete properties of SFS–FRAP aggregates. *Journal of Materials in Civil Engineering*, 28 (2).

Brand, A.S. and Roesler, J.R., 2016b. Bonding in cementitious materials with asphalt-coated particles: part I – the interfacial transition zone. *Cement and Concrete Research*, in review.

Brand, A.S. and Roesler, J.R., 2016c. Bonding in cementitious materials with asphalt-coated particles: part II – cement-asphalt chemical interactions. *Cement and Concrete Research*, in review.

Brand, A.S., Roesler, J.R., Al-Qadi, I.L., and Shangguan, P., 2012. *Fractionated reclaimed asphalt pavement (FRAP) as a coarse aggregate replacement in a ternary blended concrete pavement*. Report No. ICT-12-008, Illinois Center for Transportation, Illinois State Toll Highway Authority.

Brand, A.S., Smith, R., Roesler, J.R., Al-Qadi, I.L., and Gillen, S.L., 2012. Fresh and hardened properties of concrete with fractionated reclaimed asphalt pavement. *In*: *Proceedings of the 10th International Conference on Concrete Pavements*. Québec City, Canada, 741–754.

Capson, T. and Sorensen, A., 2013. Recycled asphalt pavement as course aggregate replacement in high strength concrete mixes. *In*: *Proceedings of the 2013 Architectural Engineering Conference*. State College, Pennsylvania: American Society of Civil Engineers.

Darter, M.I., 1977. *Design of Zero-Maintenance Plain Jointed Concrete Pavement, Volume 1: Development of Design Procedures.* Report FHWA-RD-77-111, Washington, D.C.: Federal Highway Administration.

Darter, M.I. and Barenberg, E.J., 1977. *Design of Zero-Maintenance Plain Jointed Concrete Pavement, Volume 2: Design Manual.* Report FHWA-RD-77-112, Washington, D.C.: Federal Highway Administration.

Dayioglu, A.Y., Aydilek, A.H., and Cetin, B., 2014. Preventing swelling and decreasing alkalinity of steel slags used in highway infrastructures. *Transportation Research Record*, 2401, 52–57.

Delwar, M., Fahmy, M., and Taha, R., 1997. Use of reclaimed asphalt pavement as an aggregate in portland cement concrete. *ACI Materials Journal*, 94 (3), 251–256.

Deniz, D., Tutumluer, E., and Popovics, J.S., 2010. Evaluation of expansive characteristics of reclaimed asphalt pavement and virgin aggregate used as base materials. *Transportation Research Record*, 2167, 10–17.

Dumitru, I., Smorchevsky, G., and Caprar, V., 1999. Trends in the utilisation of recycled materials and by-products in the concrete industry in Australia. *In: Concrete 99: Our Concrete Environment*, Sydney, Australia, 289–301.

Erdem, S. and Blankson, M.A., 2014. Environmental performance and mechanical analysis of concrete containing recycled asphalt pavement (RAP) and waste precast concrete as aggregate. *Journal of Hazardous Materials*, 264, 403–410.

Ferrebee, E.C., Brand, A.S., Kachwalla, A.S., Roesler, J.R., Gancarz, D.J., and Pforr, J.E., 2014. Fracture properties of roller-compacted concrete with virgin and recycled aggregates. *Transportation Research Record*, 2441, 128–134.

Federal Highway Administration (FHWA), 2006. *High Performance Concrete Pavements: Project Summary.* Report FHWA-IF-06-031, Washington, D.C.: FHWA.

Gillen, S.L., Brand, A.S., Roesler, J.R., and Vavrik, W.R., 2012. Sustainable long-life composite concrete pavement for Illinois Tollway. *In*: *Proceedings of the International Conference on Long-Life Concrete Pavements*. Seattle, Washington.

Hassan, K.E., Brooks, J.J., and Erdman, M., 2000. The Use of reclaimed asphalt pavement (RAP) aggregates in concrete. *In*: G.R. Woolley, J.J.J.M. Goumans, and P.J. Wainwright, eds. *Waste Materials in Construction*. Elsevier, 121–128.

Hossiney, N., Tia, M., and Bergin, M.J., 2010. Concrete containing RAP for use in concrete pavement. *International Journal of Pavement Research and Technology*, 3 (5), 251–258.

Hossiney, N., Wang, G., Tia, M., and Bergin, M.J., 2008. Evaluation of concrete containing RAP for use in concrete pavement. *In*: *Compendium of Papers, 87th Annual Meeting of the Transportation Research Board*. Washington, D.C.

Huang, B., Shu, X., and Burdette, E.G., 2006. Mechanical properties of concrete containing recycled asphalt pavements. *Magazine of Concrete Research*, 58 (5), 313–320.

Huang, B., Shu, X., and Li, G., 2005. Laboratory investigation of portland cement concrete containing recycled asphalt pavements. *Cement and Concrete Research*, 35 (10), 2008–2013.

Ibrahim, A., Mahmoud, E., Khodair, Y., and Patibandla, V.C., 2014. Fresh, mechanical, and durability characteristics of self-consolidating concrete incorporating recycled asphalt pavements. *Journal of Materials in Civil Engineering*, 26 (4), 668–675.

Katsakou, M. and Kolias, S., 2007. Mechanical properties of cement-bound recycled pavements. *Proceedings of the ICE - Construction Materials*, 160 (4), 171–179.

Kolias, S., 1996a. Mechanical properties of cement-treated mixtures of milled bituminous concrete and crushed aggregates. *Materials and Structures*, 29 (7), 411–417.

Kolias, S., 1996b. The influence of the type of loading and temperature on the modulus of elasticity of cement-bound mixes of milled bituminous concrete and crushed aggregates. *Materials and Structures*, 29 (9), 543–551.

Mathias, V., Sedran, T., and Larrard, F. de, 2004. Recycling reclaimed asphalt pavement in concrete roads. *In: International RILEM Conference on the Use of Recycled Materials in Buildings and Structures*, Barcelona, Spain, 66–75.

McLeod, H., 2010. *High Performance Concrete Pavements: 2009 Annual Report.* Report FHWA DTFH 71-96-TE30-KS-22, Topeka: Kansas Department of Transportation.

Mindess, S., Young, J.F., and Darwin, D., 2003. *Concrete*. 2nd ed. Upper Saddle River: Pearson Education.

Moaveni, M., Cetin, S., Brand, A.S., Dahal, S., Roesler, J.R., and Tutumluer, E., 2016. Machine vision based characterization of particle shape and asphalt coating in reclaimed asphalt pavement. *Transportation Geotechnics*, 6, 26–37.

Modarres, A. and Hosseini, Z., 2013. Mechanical properties of roller compacted concrete containing rice husk ash with original and recycled asphalt pavement material. *Materials and Design*, 64, 227–236.

Monteiro, P.J.M. and Mehta, P.K., 1986. Interaction between carbonate rock and cement paste. *Cement and Concrete Research*, 16 (2), 127–134.

Nguyen, M.I., Balay, J.M., Sauzeat, C., Di Benedetto, H., Bilodeau, K., Olard, F., and Ficheroulle, B., 2012. Accelerated pavement testing experiment of a pavement made of fiber-reinforced roller-compacted concrete. *In*: D. Jones, J. Harvey, I.L. Al-Qadi, and A. Mateos, eds. *Advances in Pavement Design through Full-scale Accelerated Pavement Testing*, Boca Raton: CRC Press, 299–311.

Okafor, F.O., 2010. Performance of recycled asphalt pavement as coarse aggregate in concrete. *Leonardo Electronic Journal of Practices and Technologies*, 9 (17), 47–58.

Van Oss, C.J., Chaudhury, M.K., and Good, R.J., 1988. Interfacial Lifshitz-van der Waals and polar interactions in macroscopic systems. *Chemical Reviews*, 88 (6), 927–941.

Patankar, V.D. and Williams, R.I.T., 1970. Bitumen in dry lean concrete. *Highways and Traffic Engineering*, 38 (1721), 32–35.

Rao, S., Darter, M., Tompkins, D., Vancura, M., Khazanovich, L., Signore, J., Coleri, E., Wu, R., Harvey, J., and Vandenbossche, J., 2013. *Composite Pavement Systems; Volume 2: PCC/PCC Composite Pavements.* SHRP2 Report S2-R21-RR-3, Washington, D.C.: Strategic Highway Research Program, Transportation Research Board.

Sachet, T., de Albuquerque, M.C.F., Balbo, J.T., and Sansone, C.E., 2011. Investigation of resistance and fracture parameters for compacted concrete with incorporation of reclaimed asphalt pavement. *International Journal of Pavements*, 10 (1-2-3), 83–93.

Sachet, T., Balbo, J.T., and Bonsembiante, F.T., 2013. Rendering the loss of strength in dry concretes with addition of milled asphalt through microscopic analysis. *IBRACON Structures and Materials Journal*, 6 (6), 933–943.

Senior, S.A., Szoke, S.I., and Rogers, C.A., 1994. Ontario's experience with reclaimed materials for use as aggregates. *In*: *Roads to the 21st Century, Proceedings of the 1994 International Road Federation Conference*. Calgary, Canada, A31–A55.

Sommer, H., 1994. Recycling of concrete for the reconstruction of the concrete pavement of the Motorway Vienna-Salzburg. *In*: *Proceedings of the 7th International Concrete Roads Symposium*. Vienna, Austria.

Sommer, H. and Bohrn, J., 1998. *Beton mit Asphalt als Zuschlag*. Bundesministerium für wirtschaftliche Angelegenheiten, Schriftenreihe Straßenforschung, Heft 476.

Su, Y.-M., Hossiney, N., and Tia, M., 2013. The analysis of air voids in concrete specimen using X-ray computed tomography. *In*: *Proceedings of SPIE: Nondestructive Characterization for Composite Materials, Aerospace Engineering, Civil Infrastructure, and Homeland Security 2013*. San Diego, California.

Su, Y.-M., Hossiney, N., Tia, M., and Bergin, M., 2014. Mechanical properties assessment of concrete containing reclaimed asphalt pavement using the Superpave indirect tensile strength test. *Journal of Testing and Evaluation*, 42 (4), 1–9.

Texas Transportation Institute (TTI), 2015. *Validation of RAP and/or RAS in Hydraulic Cement Concrete*. College Station: Texas A&M Transportation Institute. http://trid.trb.org/view.aspx?id=1359618

Wojakowski, J.B., 1998. *High performance concrete pavement*. Report No. FHWA-KS-98/2, Kansas Department of Transportation, Topeka.