Validation of RAP and/or RAS in Hydraulic Cement Concrete: Technical Report

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16. Abstract
The increasing maintenance and rehabilitation actions lead to considerable amounts of reclaimed asphalt pavement (RAP) left in stockpiles in the United States. The possible use of RAP in Portland cement concrete (PCC) as aggregate replacement not only would help dispose of excess RAP stockpiles, but also provide a reduction in virgin aggregate consumption in PCC, which brings significant benefits from both economic and environmental standpoints. In this project, the previous findings on the mechanical properties and durability of RAP-PCC reported in the literature were validated. The microstructures and crack propagation in the RAP-PCC system were investigated through several advanced techniques such as optical microscope, x-ray CT, and scanning electron microscope. Performance evaluation of RAP-PCC slab by using pavement performance software and the life cycle assessment models were also conducted. Finally, the guidelines and implementation plan were provided in order to facilitate the use of PCC containing RAP in the field. The major conclusions from this project are 1) The coarse RAP with suitable gradation containing sufficient intermediate size particles can help make dense graded concrete. The dense graded RAP-PCC showed better workability and mechanical properties compared to the other gap graded RAP-PCC. 2) The major weak point of the RAP-PCC system is the asphalt. Asphalt cohesive failure (i.e., crack easily propagate through the asphalt layer around the RAP particles) is the major failure mechanism. 3) Compared with the material production for plain PCC pavement, the production of materials for constructing RAP-PCC pavements (either full-depth or two-lift) was more economical and consumed less amounts of energy. It released less amounts of air pollutants, greenhouse gases, and toxic materials. It also led to less land use and water withdrawals and 4) The idea of using RAP-PCC as the bottom lift in a two-lift PCC pavement can maximize the RAP usage without compromising the pavement performance or compromise within the permissible limits.

17. Key Words
RAP, RAS, PCC, TxCRCP, Pavement, Concrete, Asphalt, Reclaimed, Recycled, Shingles

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DISCLAIMER

This research was performed in cooperation with the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the FHWA or TxDOT. This report does not constitute a standard, specification, or regulation. The Research Scientist in charge of the project was Dr. Anol K. Mukhopadhyay.

The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

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CHAPTER 1. INTRODUCTION

BACKGROUND

Reclaimed or recycled asphalt pavement (RAP) and recycled asphalt shingles (RAS) have been widely used in hot mix asphalt (HMA) in Texas. However, a high volume of RAP is still available in stockpiles along the Texas Department of Transportation's (TxDOT's) highways or at HMA concrete producers' plants, in spite of use by the asphalt industries. Ground RAS from manufacturers and post-consumer uses are also available. The possible use of RAP and RAS in Portland cement concrete (PCC) not only would help dispose of excess RAP and RAS, but also provide a cost reduction for aggregates in hydraulic cement concrete.

LITERATURE REVIEW

RAP and RAS and Their Uses in HMA

The asphalt paving engineering community has always advocated recycling, including RAP, RAS, tires, etc. This promotes substantial cost savings and conservation of aggregates and asphalt. A brief discussion on the use of RAP/RAS in HMA is provided.

Recycled Asphalt Pavement

Over 90 percent of U.S. highways and roads are constructed with HMA (Copeland 2011), and the increasing maintenance and rehabilitation result in considerable amounts of RAP left in a stockpile. The issues on how to use this material have become more popular in the United States with the increasing demands of sustainable development. RAP is generated when asphalt pavements are removed for reconstruction, resurfacing or to obtain access to buried utilities (Chesner et al. 1998). RAP contains mainly aggregate with adhering aged asphalt film and can be successfully reused for new constructions. Hansen and Copeland (2013) conducted surveys of RAP usage in the United States. Their results show that the overwhelming majority of RAP is used in HMA or warm-mix asphalt (WMA), which is considered to be an effective way to reduce RAP stockpiles. However, most department of transportations (DOTs) only allow the RAP fraction in the HMA up to 20 percent, because the addition of too much RAP is likely to cause serious reduction in pavement performance. Besides HMA/WMA application, RAP can also be used in the base and cold mix. RAP has been put into landfills as well, but those amounts are fairly small (Figure 1).

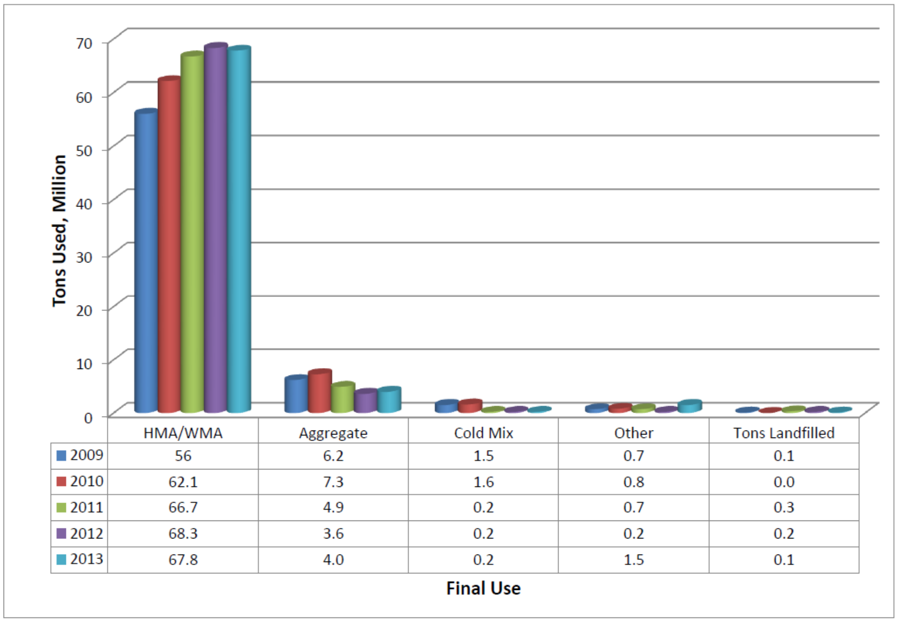


Figure 1. RAP with Different Usage (Million Tons) (Hansen and Copeland 2013).

Unfractionated RAP usually contains more fines than natural aggregate due to generation of uncontrolled fines in milling and crushing process. RAP can be typically obtained by cold milling or ripping followed by crushing. The RAP obtained from milling is generally finer and denser than that from ripping & crushing (Chesner et al. 1998). This large amount of fines in the RAP is likely to result in reduction in load bearing capacity of a mix. As a result, it is often not recommended for constructing the parts of road that are crucial to the road's loading-bearing ability using RAP with large amount of fines (Robinson et al. 2004). Another issue in the use of RAP is the presence of aged asphalt. Generally, the asphalt content of RAP ranges between 3 and 7 percent by weight (Chesner et al. 1998). Because asphalt becomes stiffer with time when exposed to atmosphere as light constituent of asphalt volatilizes and oxides, the hardened aged asphalt might have a higher rutting resistance but is usually more vulnerable to cracking distresses. Asphalt recycling agents have been often added to RAP to restore aged asphalt to desired specifications (Kandhal and Mallick 1998). RAP can be collected from various sources, whose properties can vary significantly depending on the service life and ambient environment. Usually, RAP collected from most wearing surface exhibits relatively high viscosity. Because of the variability in RAP properties, RAP material needs to be characterized before being used. Most agencies extract the binder from RAP and determine aggregate gradation, asphalt content, and asphalt viscosity at 60°C, separately.

While the use of RAP in HMA is not the interest of this research, a brief overview of the investigations is included here. Though no problems with mixing and compacting asphalt concrete mixture with RAP (Yamada et al. 1987), adding RAP increased void in mineral aggregate and void filled with asphalt (Daniel and Lachance 2005). Based on Li et al. (2008), the RAP modified asphalt concrete had higher dynamic modulus (E*) than the control with greater influence at high temperature. For the low temperature fracture resistance, the addition of RAP had negative effect.

Reclaimed Asphalt Shingles

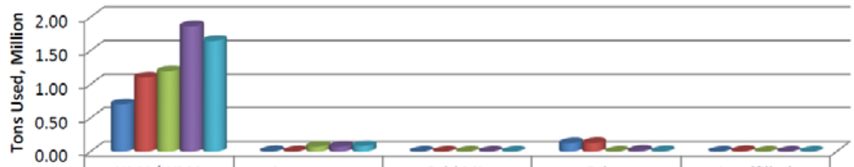
RAS are other recycled materials that have been successfully used in the HMA construction. Two main types of RAS are used in roof construction based on their base compositions: organic cellulose and fiberglass. Table 1 lists their compositions.

Table 1. Composition of RAS.

Type	Composition	% Weight
Organic	Asphalt	30~35%
	Mineral fiber	5~15%
	Mineral and ceramic-coated granules	30~50%
Fiberglass	Asphalt	15~20%
	Felt	5~15%
	Mineral filler	15~20%
	Mineral and ceramic-coated granules	30~50%

RAS can be classified as manufacturer waste shingles and tear off shingles based on the source they are from. Manufacturer waste is known as roofing shingle tabs or punch-outs, and it includes out-of-spec, miscolored, or damaged shingles (Griffiths and Krstulovich Jr. 2002). Tear off shingles are consumer aged waste from the roofs, which usually have ages ranging from 14 to 21 years (Hassan et al. 2013). Tear-off asphalt shingles have higher binder content than manufacture waste asphalt shingles (Zhou et al. 2011).

Based on Newcomb et al. (1993), the ground RAS had particle sizes ranging about 5 to 30 mm. The agglomeration of the particles would add difficulty to gradation analysis. The specific gravity of the RAS was around 1.30. Hassan et al. (2013) investigated the rheological properties and molecular fractions of the extracted aged asphalt from RAS of different sources. He also found manufacturer waste shingles had lower asphalt content than tear-off shingles. The extracted RAS binder was graded as PG 118 or higher, but the lower temperature grade was not detected because of the high stiffness. Similar to RAP, RAS is also mainly used in producing HMA and WMA. RAS materials generally contain 15 to 35 percent of asphalt binder. As a result, RAS can serve as a good source of asphalt binder and this could provide an annual savings of $1.1 billion for asphalt industry (Northeast Recycling Council 2007). For the application in HMA, manufacturer waste is used as an asphalt modifier and often improves temperature susceptibility and rut resistance, while tear-off shingles are less popular because they contain foreign materials and affect mixture properties (Griffiths and Krstulovich Jr 2002). The use of negligible amount of RAS in cold mix, landfill and base was also reported as shown in Figure 2 (Hasen and Copeland 2013).



	HMA/WMA	Aggregate	Cold Mix	Other	Landfilled
2009	0.70	0.01	0.00	0.12	0.00
2010	1.10	0.00	0.00	0.13	0.01
2011	1.19	0.07	0.00	0.00	0.00
2012	1.86	0.07	0.00	0.01	0.00
2013	1.65	0.08	0.00	0.01	0.00

Final Use

Figure 2. RAS with Different Usage (Million Tons) (Hansen and Copeland 2013).

State of the Practice and State of the Art on the Use of RAP/RAS in PCC

Various aspects related to the use of RAP/RAS in PCC are critically evaluated based on the published literatures and an email survey sent to the different districts in Texas. These aspects are presented in the following sections:

- Effects of RAP/RAS on combined aggregate gradation.
- Lab investigations on concrete containing RAP.
- Field investigations on concrete containing RAP.
- Physical and chemical interactions between asphalt and cement.
- Challenges and limitations of using RAP/RAS in PCC applications.

Effects of RAP/RAS on Combined Aggregate Gradation

The gradation of RAP is often very different from the gradation of the original virgin aggregate used to make HMA. The RAP gradation depends on production process and ambient environmental conditions. Usually, the portions of the intermediate (particles passing the 3/8 in. sieve and retained on the #8 sieve) and coarse fractions (particles retained on 3/8 in. sieve) in the RAP are much higher than the gradation in virgin concrete coarse aggregate. Based on the paper published by Huang et al. (2006) and Al-Oraimi et al. (2009), the coarse RAP is finer than the coarse limestone while the fine RAP is coarser than the sand, as shown in Figure 3 and Figure 4. For a better gradation control, RAP is often fractionated into different stockpiles for different purposes. The Illinois State Toll Highway Authority reprocessed their RAP to produce both coarse RAP and fine RAP stockpiles. They used a #4 sieve to separate the fine and coarse fraction. The coarse fraction underwent an additional screening by using 1/2 in. or 5/8 in. sieves to remove larger-size agglomerated particles and produce the coarse RAP (Brand 2012).

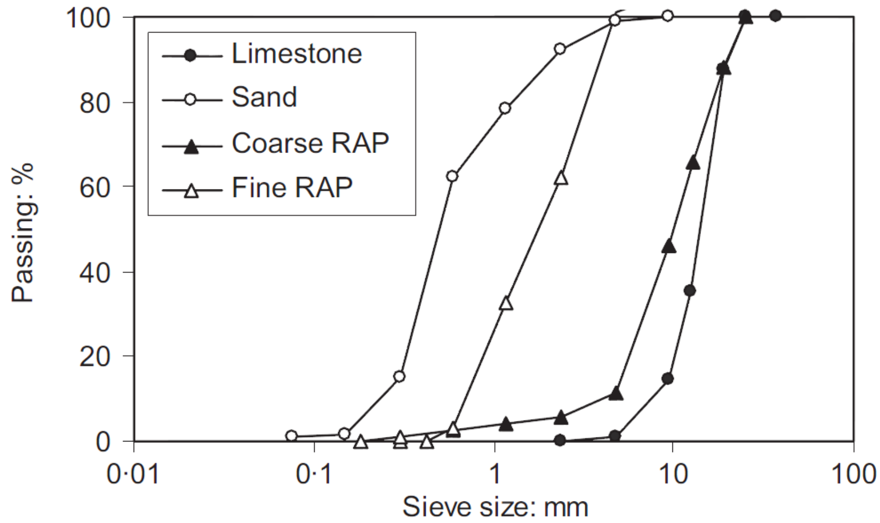


Figure 3. Gradations of Limestone Coarse Aggregate, Sand, and RAP Materials (Huang et al. 2006).

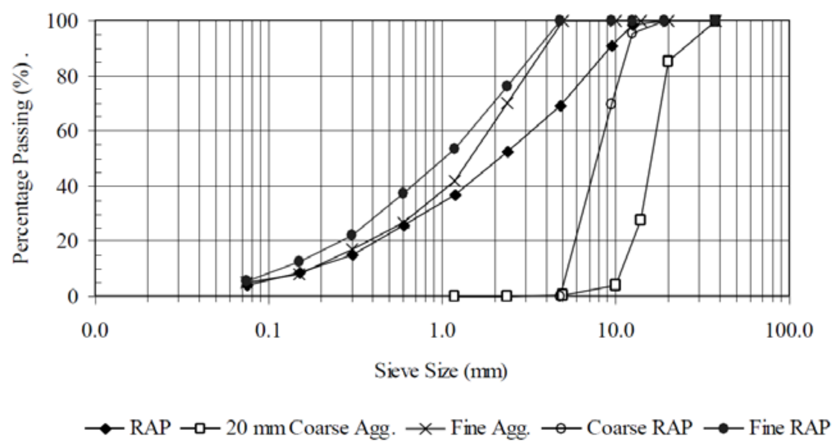


Figure 4. Grain Size Distribution for Different Aggregate and RAP Materials (Al-Oraimi et al. 2009).

Table 2 presents the results of sieve analysis of the RAP samples collected in Texas by Zhou et al. (2011). The coarse RAP contains 47.5 percent of intermediate aggregate, and the binder content of the coarse RAP is much lower than that of fine RAP. Because it contains a large fraction of intermediate aggregates, the RAP material can be introduced to the conventional concrete gradation to make concrete dense graded, as most of the conventional concrete is gap graded with a limited amount of intermediate aggregate particle sizes. Based on a detailed synthesis study (Richardson et al. 2005), the potential benefits resulting from an optimized dense gradation can be significant. They pointed out that the use of a more well graded aggregate blend would result in less paste and reduced concrete shrinkage, greater strengths, better pumpability, and enhanced finishability. They also mentioned "well graded mixtures tend not to have as many problems as gap graded mixes in terms of pavement edge slump, segregation during vibration, finishing, raveling at joints, and wear resistance." Appendix A gives an overview of the concrete aggregate gradation optimizations, among which the Shilstone approach is highlighted and credited. The Shilstone optimization approach (Shilstone 1990) provided major guidance for the aggregate gradation design in Chapter 2.

Table 2. Dry Sieve Analysis of the RAP Samples Collected in Texas (Zhou et al. 2011).

Sieve Size	Ranges of Cumulative % Passing of RAP Samples			
	TxDOT Owned Stockpiles, Unfractionated RAP	Contractor Owned Stockpiles, Crushed RAP	Contractor Owned Stockpile, Crushed Coarse RAP	Contractor Owned Stockpile, Crushed Fine RAP
¾ in.	100.0	100.0	100.0	100.0
½ in.	97.7–99.2	98.1–98.4	97.5	99.8
3/8 in.	91.4–92.0	91.4–92.7	84.5	98.8
#4	65.1–72.2	67.5–74.5	54.5	85.2
#8	45.0–46.8	46.5–56.3	37.0	58.7
#16	32.9–35.0	35.0–44.3	26.2	45.2
#30	24.6–28.1	28.3–34.2	19.8	38.0
#50	18.0–19.4	22.3–24.0	14.5	28.1
#100	11.8–12.0	13.1–15.8	7.5	15.1
#200	7.5–7.6	8.1–11.6	3.6	7.5
AC (%)	5.4–7.9	4.4–5.3	2.8	5.3

In a Florida Department of Transportation (FDOT) project completed by Tia et al. (2012), a detailed study to investigate the aggregate gradation with addition of RAP has been conducted. The research team selected four FDOT approved RAP. They used a No.4 sieve to fractionate RAP into coarse and fine fractions. The virgin aggregates (both coarse and fine) in the PCC mixtures were replaced by the selected RAP materials at replacement levels of 0 percent, 20 percent, 40 percent, 70 percent, and 100 percent. The researchers evaluated the combined aggregate gradation based on the approach of mix design optimization by Shilstone (1990) and made the following conclusions:

- Adding RAP with adequate intermediate size particles (passing 3/8 in. but retaining on No. 8) facilitated improvement of combined aggregate gradation (i.e., achieving close to a dense aggregate gradation).
- The fineness modulus increased with an increasing amount of RAP
- Coarseness factor (CF), individual percent retained (IPR), and 0.45 power chart analysis suggested 40 percent RAP as the optimum level of replacement.

RAS are usually fine materials. Zhou et al. (2012) used RAS from different sources for their investigation. Their sieve analysis (Table 3) showed 1) the RAS primarily consisted of fine aggregates, and 2) the tear-off asphalt shingles have slightly finer gradations than manufacture waste shingles.

Table 3. Dry Sieve Analysis Results of Seven Processed RAS Materials (Zhou et al. 2012).

RAS	Sieve No.	#1	#2	#3	#4	#5	#6	#7	Average	Standard Deviation
A Blended (manu.+tear)	1/2”	100	100	98	99	100	100	100	100	0.6
	3/8”	99	98	96	99	99	99	99	98	1.1
	#4	91	82	87	91	88	88	90	88	3.1
B Manufacture waste	1/2”	100	100	100	100	100	100	100	100	0.0
	3/8”	100	100	100	100	100	100	100	100	0.1
	#4	85	80	89	93	87	89	90	87	4.1
C Manufacture waste	1/2”	99	99	99	100	100	100	99	100	0.2
	3/8”	97	96	97	97	98	96	96	97	0.8
	#4	78	77	78	74	82	68	67	75	5.4
D Manufacture waste	1/2”	100	100	100	100	99	100	99	100	0.5
	3/8”	94	96	97	97	97	96	94	96	1.5
	#4	80	83	85	84	84	83	81	83	1.7
E Tear-off	1/2”	100	100	100	100	100	100	100	100	0.1
	3/8”	97	98	95	92	97	96	96	96	2.0
	#4	85	90	82	76	88	85	85	84	4.5
F Tear-off	1/2”	100	100	100	100	100	100	100	100	0.1
	3/8”	99	100	99	100	100	100	99	100	0.2
	#4	81	86	82	84	88	86	84	84	2.3
G Tear off	1/2”	100	100	100	100	100	100	99	100	0.4
	3/8”	100	100	100	100	100	100	98	100	0.9
	#4	94	93	95	94	93	94	89	93	2.2

Lab Investigation of the Mechanical Properties and Durability of RAP-PCC

Various researches have investigated the feasibility of using RAP in PCC in different civil materials laboratories inside and outside of the United States. During the past several years, several state funded researches on this topic were successfully completed. Tia et al. (2012) from the University of Florida evaluated the mechanical effects of RAP on cement concrete properties. In this FDOT funded project, the research team used four different types of RAP to replace both coarse aggregates and fine aggregates in the conventional concrete mix. The RAP replacement levels were selected as 20 percent, 40 percent, 70 percent, and 100 percent. The state of Illinois fractionated RAP into coarse and fine stockpiles. While the fine RAP is widely used in HMA, numerous coarse RAP stockpiles remain untouched, generating large disposal costs. The Illinois State Toll Highway Authority (Tollway) initiated a study to evaluate the application of the coarse fractionated RAP in pavement concrete (Brand 2012) in terms of both mechanical properties and durability. In this project, the coarse RAP was served as a partial replacement of virgin coarse aggregate in a ternary blend concrete containing cement, slag, and fly ash. In another investigation, Berry et al. (2013) studied the feasibility of RAP as aggregate in PCC. This research used a statistical experimental design procedure to determine the mix designs that warrant further evaluation including mechanical and durability tests. Two RAP concrete mix designs were finalized and evaluated. This section presents a detailed review of related literatures.

Mechanical Properties

Properties of Fresh Concrete

The properties of fresh concrete are of great importance because they will be directly related to the choice of equipment for handling and consolidation and will have significant influences on properties of hardened concrete. These properties include slump, air void, unit weight, and temperature.

Slump

Slump is an indicator of concrete workability. The introduction of RAP to concrete caused significant reduction in slump according to most investigators (Al-Oraimi et al. 2009; Delwar et al. 1997; Huang et al. 2005; Okafor 2010; Tia et al. 2012). The larger the amount of RAP in the mix the smaller the slump is. Huang et al. (2005) found coarse RAP aggregate had fewer negative effects on concrete workability than fine RAP aggregate. This observation was likely due to the higher asphalt content in the fine RAP than the coarse RAP. Interestingly enough, they also reported that the mix made with both coarse and fine RAP had a higher slump than the control mix.

Air Void, Unit Weight, and Temperature

It seems that adding RAP to concrete would not have a significant impact on air void (Hossiney et al. 2010; Huang et al. 2005), but the decrease in unit weight was apparent (Al-Oraimi et al. 2009; Delwar et al. 1997; Tia et al. 2012). The decrease in unit weight is reasonable because asphalt is lighter compared with aggregate. The fresh concrete mix containing RAP had a slightly higher temperature compared to the plain one, but was still within the normal range (Tia et al. 2012).

Properties of Hardened Concrete

Mechanical properties of hardened concrete are major indicators to manifest the feasibility of using RAP as aggregate replacement in pavement concrete. The properties of hardened concrete reviewed in this section include compressive strength, modulus of elasticity (MOE), and Poisson's ratio, flexural strength, splitting tensile strength (STS), toughness and ductility, and coefficient of thermal expansion (CoTE).

Compressive Strength

Compressive strength is the most commonly used parameter to characterize concrete. Several studies were conducted, and they all indicated that the addition of RAP would reduce concrete compressive strength (Al-Oraimi et al. 2009; Delwar et al. 1997; Hassan et al. 2000; Hossiney et al. 2010; Huang et al. 2005; Katsakou and Kolias 2007; Mathias et al. 2004; Okafor 2010; Tia et al. 2012; Topcu and Isikdag 2009). Among these investigations, Huang et al. (2005) evaluated the concrete mixes made with different sized RAP. They concluded that coarse RAP caused less reduction in compressive strength than fine RAP did, which is indicated in Figure 5. Okafor (2010) only replaced 100% coarse aggregate with RAP in his study. He tested the compressive strengths of the mixtures using different water/cement (w/c) ratio and mix proportions. He believed RAP concrete could hardly yield a compressive strength above 25 MPa because of the limited strength of the asphalt-mortar bond (Figure 6). As shown in Figure 7, Hossiney et al. (2010) evaluated the effects of RAP replacement level (both coarse and fine RAP replacement) on concrete compressive strength. Their results and the results for the FDOT project completed by Tia et al. (2012) showed that concrete with larger amounts of RAP would have lower compressive strength.

According to the compression results from Tia et al. (2012), researchers concluded: 1) The trend of strength development was similar between RAP concrete and plain concrete; and 2) Concrete mixtures with 100 percent RAP replacement (both coarse and fine) exhibited around 70 percent reduction in compressive strength. The project conducted in Illinois replaced virgin coarse aggregate with up to 50 percent coarse RAP. Although the compressive strength decreased by 39 percent for the 50 percent RAP replacement level, the research team believed up to 50 percent coarse RAP in a concrete in the mix may still be feasible to meet the DOT strength requirement for pavement application Brand (2012). The Montana DOT research successfully produced RAP concrete with compressive strength that met the specification as well. One of their qualified mix contained 50 percent of fine RAP and 100 percent of coarse RAP (they named HR mix), and the other had 25 percent fine RAP and 50 percent coarse RAP in the concrete (named HS mix) (Berry et al. 2013).

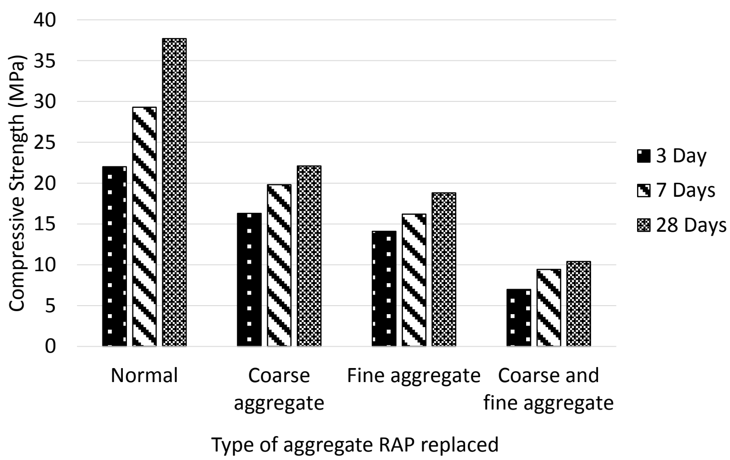


Figure 5. Effect of Aggregate Size on Compressive Strength (Re-plotted from Huang et al. 2005).

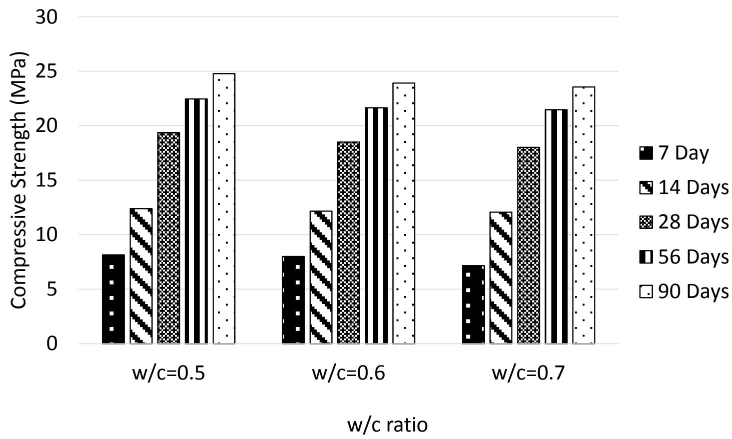


Figure 6. Effect of w/c Ratio on Compressive Strength (Re-plotted from Okafor 2010).

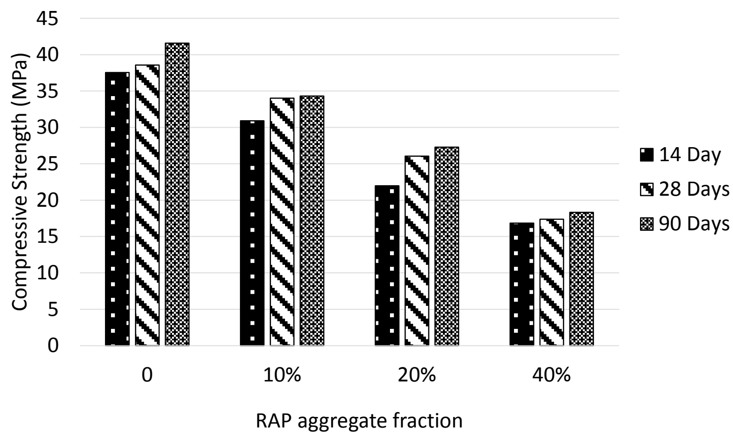


Figure 7. Effect of RAP Aggregate Fraction on Compressive Strength (Re-plotted from Hossiney et al. 2010).

Flexural Strength

Flexural strength, or modulus of rupture (MOR), actually indirectly measures concrete tensile strength. According to Katsakou and Kolias (2007), the rate of reduction in flexural strength was slower than the rate of reduction in the corresponding compressive strength. Similar with compressive strength observations, Huang et al. (2005) found that coarse RAP aggregates caused less reduction in flexural strength than fine aggregates. From Tia et al. (2012), the maximum reduction was reported as 50 percent when 100 percent aggregates were replaced by the RAP. However, although the flexural strength of the concrete made of RAP was lower than that of the conventional concrete, the computed stress to strength ratio for some of the RAP concrete was lower than that for the conventional concrete. Both the Illinois Tollway project and the Montana DOT project obtained RAP concrete with qualified flexural strengths (Berry et al. 2013; Brand 2012).

STS

STS is another indirect measurement of concrete tensile strength. Tia et al. (2012) concluded the STS of RAP concrete decreased with increase of RAP fraction in the mix. A maximum reduction of 60 percent in STS was obtained from their results. Mathias et al. (2004) investigated the STS behavior of RAP concrete under different temperatures. Their results confirmed that RAP concrete had decreased STS, and temperature had more significant influences on strength reduction at higher RAP content. In the Illinois Tollway project report, Brand obtained a 52 percent STS reduction when 50 percent of the coarse RAP was added in a cement-slag-fly ash ternary blend (Brand 2012).

MOE and Poisson's Ratio

It is not surprising to see that several investigators obtained lower MOE of concrete made with RAP compared with normal concrete (Al-Oraimi et al. 2009; Katsakou and Kolias 2007; Mathias et al. 2004; Tia et al. 2012; Topcu and Isikdag 2009), because asphalt is a much softer material than cement paste in room temperature. The negative effect of RAP on concrete MOE was significant. The maximum reduction could be up to 70 percent, which was reported by Tia et al. (2012) when they compared concrete made with 100 percent RAP aggregates (both coarse and fine) with normal concrete at 90 days. According to the results obtained by Brand (2012), the addition of 50 percent coarse RAP reduced the MOE by 30 percent. Berry et al. (2013) reported a reduction of 46 percent in elastic modulus for their HR mix (100 percent coarse RAP replacement and 50 percent fine RAP replacement) and a reduction of 17 percent for their HS mix (50 percent coarse RAP replacement and 25 percent fine RAP replacement) at the age of 28 days by comparing the RAP concrete with the control concrete. For RAP concrete's Poisson's ratio, few tests had been conducted, and probably the most detailed data was recorded by Tia et al. (2012). According to their results, the researchers found:

- The Poisson's ratio increased when RAP percentage increased.
- The values for concrete made with no RAP, intermediate RAP fraction (20 percent, 40 percent, and 70 percent), and high RAP fraction (100 percent) were between 0.20 and 0.25, close to 0.25, and between 0.25 and 0.30, respectively.
- Poisson's ratio increased with increased curing days.

Drying Shrinkage and CoTE

Drying shrinkage and CoTE are coefficients that highly affect the concrete cracking initiation and propagation. Results from Topcu and Isikdag (2009) showed replacing all virgin aggregates with RAP resulted in a 40 percent increase in shrinkage, and the authors claimed this phenomenon was due to less restraint in cement paste because of lower MOE when RAP was added. Tia et al. (2012) found, in general, the shrinkage of concrete via air curing process increased when the RAP fraction increased. For concrete undergoing moist curing process, the RAP concrete specimen showed significant length change before 28 days, but the change after 28 days was small. From Brand (2012) results, there was no clear trend of length changes in free shrinkage. However, the restrained ring shrinkage tests indicated that adding the coarse RAP reduced the restraint-induced shrinkage strains. For the investigations conducted in Montana, both of the two mixes did not exhibit excessive deformations associated with shrinkage (Berry et al. (2013)). The CoTE of concrete made with RAP at different fraction was also investigated by Tia et al. (2012) in accordance with AASHTO TP-60-00 standard test method. Authors drew a conclusion that the addition of more RAP to concrete mix would result in higher CoTE.

Toughness and Ductility

One positive influence of using RAP is that the addition of RAP in concrete improves the toughness and ductility. Toughness measures the ability of a material to absorb energy, which can be determined by integrating the stress-strain curve. Huang et al. (2005) stated that the asphalt that exists in RAP would form a thin film at the interface of cement mortar and aggregate, and crack would propagate along the mortar-asphalt-aggregate interface rather than break the aggregate, resulting a dissipation of more energy (Figure 8). Their STS test results indicated that the RAP concrete specimen maintained the peak load for a longer time and had higher toughness than normal concrete (Figure 9). Tia et al. (2012) conducted flexural beam tests to determine the toughness and ductility. Although the concrete made with RAP failed at lower stress, the failure strain and the area under stress-strain curve increased with the increasing content of RAP. Hassan et al. (2000) also concluded that the addition of RAP to concrete improved ductility and shock absorbent properties based on their flexural beam tests.

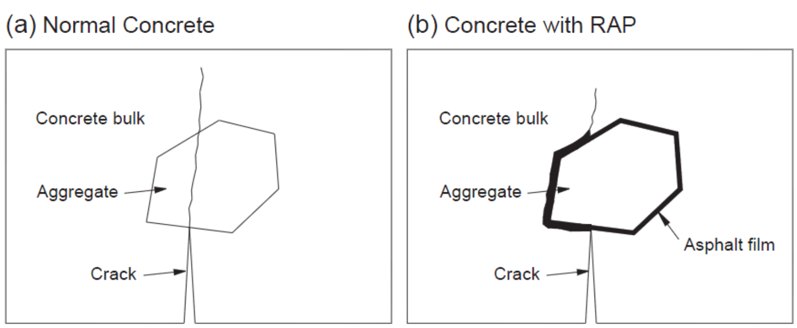


Figure 8. Crack Propagation in Concrete and Concrete with RAP (Huang et al. 2005).

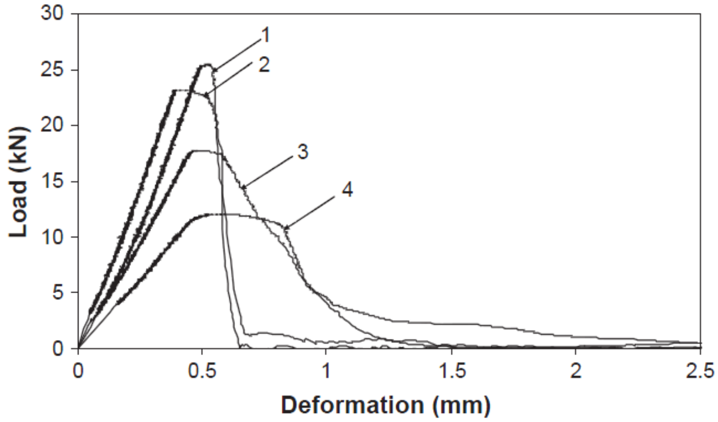


Figure 9. Typical Load Deformation Curves of Concrete Specimens under STS Test at 14 Days: 1. Control Concrete; 2. Concrete Containing 100 Percent Coarse RAP Only; 3. Concrete Containing 100 Percent Fine RAP Only and 4. Concrete Containing 100 Percent Coarse and Fine RAP (Huang et al. 2005).

Relationship between Mechanical Properties

The concrete compressive strength is the easiest parameter to obtain in the lab and field. The American Concrete Institute (ACI) adopted equations to calculate other properties by using compressive strength. Based on the experimental results, Tia et al. (2012) developed new equations to estimate properties of concrete made with RAP. Table 4 summarizes equations for RAP concrete with comparisons of the ACI equations.

Table 4. Comparisons between the ACI Equations and Tia et al. (2012) Equations.

Mechanical property	ACI equations for normal concrete	Tia et al. (2012) equations for RAP concrete	Feasibility of using ACI equations to predict RAP concrete
Flexural strength (R)	$R = 7.5 \times f_c^{0.5}$	$R = 9.25 \times f_c^{0.5}$	ACI equation underestimates the prediction of the RAP concrete
MOE (E_c)	$E_c = 57 \times f_c^{0.5}$	$E_c = 54.665 \times f_c^{0.5}$	ACI equation overestimates the prediction of the RAP concrete
STS (f_{ct})	$f_{ct} = 6.7 \times f_c^{0.5}$	$f_{ct} = 1.5623 \times f_c^{0.6791}$	No conclusion made by the authors

f_c – compressive strength

Durability

Durability is another important aspect to judge the performance of concrete. Especially when the reclaimed asphalt concrete is involved in the concrete, it is very necessary to evaluate the mixture's durability such as rapid chloride permeability, freeze-thaw resistance, and abrasion resistance. A review of the published results on the durability of RAP concrete is presented as follows, although such results are relatively limited compared to those for the mechanical properties.

Rapid Chloride Permeability

The data for the RAP concrete rapid chloride penetration test are limited. Brand (2012) did this test for their Illinois tollway project based on the American Association of State Highway and Transportation Officials (AASHTO) T277. They concluded that replacing virgin coarse aggregate with fractionated coarse RAP at different replacement level yielded very similar rapid chloride permeability results, ranging from very low to low for all samples. In 2013, Berry et al. (2013) reported the chloride permeability results (ASTM C 1202) for their HR and HS mixes. Based on their results, a moderate level of chloride ion penetrations were reported for both HR and HS mixes. From the comparison between the HR and the HS mix, a larger amount of RAP in the mix caused a higher chloride ion penetrability.

Freeze/Thaw Resistance

According to Brand (2012), the durability factor decreased with the increase of coarse RAP fraction. But still, all their results were above the limiting value of 60, which were qualified by the AASHTO T161 specification. In their tests, they found that the samples with 20 percent RAP content had similar freeze/thaw durability with the controls, but both the 35 percent and 50 percent coarse RAP mixes experienced greater reductions in durability factor and mass loss than the control concrete. Berry et al. (2013) obtained an average durability factor of 94 for the HR mix and a factor of 98 for the HS mix at 300 freeze/thaw cycles, while the control mix had a value of 100 with no loss of stiffness. Both of the mixes had less than 1 percent mass loss. The observation that the HR mix had a slightly smaller durability factor and a slightly higher mass loss indicated that a larger amount of RAP is likely to have a more significant reduction in the freeze/thaw resistance.

Abrasion

To evaluate the abrasion resistance of the concrete with RAP, Berry et al. (2013) first used a 22-lb load to evaluate the abrasion properties of the HR and HS mix designs according to ASTM C 944. The resulting average mass loss turned out to be 0.3 g for both cases, and both of the wear depths were less than 1.0 mm. These results indicated the RAP concrete samples performed well, so a further investigation was conducted by using a 44-lb load. Again, little weight loss and wear depth were reported.

Field Investigations of PCC Containing RAP

Due to the observations that adding RAP to PCC had significant detrimental effects on mechanical properties from different lab investigations, only a few field tests have been conducted to evaluate the feasibility of use of PCC containing RAP. Davio summarized the TxDOT experience using RAP in various application. Table 5 lists the reported field applications of using RAP-PCC mixtures as concrete paving materials. However, no detailed further information have been obtained.

Table 5. TxDOT Experience with Using RAP in PCC (Davio).

District Name	Construction	Results	Time - Installed	Location
Beaumont	Paving materials-PCC	Good	1994	Chambers
Beaumont	Paving materials-PCC	Excellent	1987	Jasper
Childress	Paving materials-PCC	Good	1987	Briscoe (SH 89), Childress (US 287), Hall (US 287)

In a field demonstration in Montana, two 10-inch thick RAP-PCC slabs, one made of the HR mix and another one made of the HS mix, were placed on a roadway at the MSU/WTI Transcend Research Facility. No logistical issues were experienced during RAP-PCC production and slab construction. No observable damage (cracking or spalling) and excessive shrinkage or curling were found on the test slabs during two-year monitoring period (Berry et al. 2015).

The Illinois State Toll Highway Authority has begun a 15-year program named move Illinois for roadway reconstruction, rehabilitation, and expansion. From their published lab results, concrete containing coarse fractionated RAP at up to 50 percent replacement level can meet existing Tollway durability and strength performance standards (Brand 2012). According to Bentsen et al. (2013), the Tollway's first field production and placement of RAP concrete was performed in October 2010, as part of the reconstruction of the Milwaukee Avenue ramps on Tri-State Tollway (I-94). The pavement consisted of a 9-in. thick concrete with 28 percent washed, coarse fractionated RAP (FRAP), and a 3-in. thick HMA overlay. The concrete was produced with 655 lb/cy of cementitious content, including 79 percent of cement and 21 percent of fly ash. The Illinois Tollway then built another two-lift composite concrete pavement containing dirty fractionated RAP. The pavement was placed on the Reagan Memorial Tollway (I-88) in 2012, and the total thickness was 11.25 in. The contractor used a ternary concrete mixture with 35 percent supplementary cementitious material and 20 percent dirty fractionated RAP with an optimized aggregate gradation for the bottom lift, which was covered by a standard virgin aggregate non-ternary PCC layer. These two field results show that this method can provide a viable way to enhance sustainability with no negative impacts on cost or performance (Bentsen et al. 2013; Gillen et al. 2012).

Actually, Iowa State already constructed a two-lift trial section in the 1970s. It was an 11-in. composite section with a 7-in. lower course and a 4-in. upper course. The lower course used RAP and recycled concrete pavement as aggregate sources. Based on the field experience, the authors believed that using existing concrete on reconstruction projects as an aggregate source can be feasible (Bergren and Britson 1977).

In 2001, the Maine Department of Transportation blended portland cement, RAP milled from the highway, and virginal aggregates to reinforce and stabilize road shoulders adjacent to the existing old concrete slabs. This innovative method turned out to be very successful, provided the shoulder preservation and stabilization is a major concern of the design and the extra cost is considered worthwhile (Thompson 2007).

According to Davio, the Beaumont District used RAP with PCC to create base for add on lane on SH 87 in 1995. He mentioned the result was excellent, but no further information was obtained.

Interaction between Asphalt and Cement

The interaction physically or chemically between RAP and cement paste is one of the important aspects of this study. The mechanism that whether asphalt interacts with cement hydration and how asphalt affects development of interfacial transition zone (ITZ) are extremely important to understand the observations of the behaviors of concrete containing RAP. However, very limited amount of researches have been published on this field. Recently, Brand and Roesler (2017) published their detailed work on RAP-PCC microstructure studies. In the Part I of their paper (Brand and Roesler 2017), they concluded that the reduction in the RAP-PCC mechanical strengths was due to its higher porosity, larger ITZ width and less CH at cement-RAP interface based on image analysis of backscattered electron micrographs. In the Part II paper of their study (Brand and Roesler 2017), in order to improve the cement-asphalt bond in the RAP-PCC system, they treated RAP with several chemical oxidative but the bonding improvement was not very significant. Based on surface free energy measurement and visual inspections of beam sample failure surface, they concluded the asphalt cohesion failure was the dominant failure mode in the RAP-PCC system. According to the findings from Part I and Part II of their paper, the reduced RAP-PCC strength and modulus were contributed to a combined effect of higher porosity in ITZ and the preferential asphalt cohesion failure.

A project entitled *Durability, Ductility and Bond Strength of Portland Cement Concrete with Recycled Asphalt Pavement as Partial Replacement for Coarse Aggregate* funded by Idaho Transportation Department is supposed to be completed in the early 2015. Once the project final report is published, it will provide useful information on the bond strength between reinforcing steel and concrete mixtures with various RAP replacement percentage.

Challenges and Limitations of Using RAP/RAS in PCC Applications

The challenges and limitations of using RAP/RAS in PCC applications can be summarized as follows.

Mixing Problems

Due to the existence of aged asphalt binder, RAP particles may bond together and form agglomerations (a coarser particle consisting of two or more RAP particles). The presence of agglomerated particles make a reliable RAP characterization challenging (especially determining aggregate gradation and Sp. Gr.), which can leads to a non-uniform distributions of RAP in concrete. However, most published literature did not report serious agglomeration problems, and it seems that the RAP clumps can be easily separated by conventional mixing equipment and manners. Brand (2012) determined the agglomerated particles in his coarse FRAP sample. He found approximately 14.2 percent of particles were agglomerated, but no significant clumps were found after mixing.

Mechanical Properties and Durability Reductions

Brand (2012) conducted a thorough literature review on the effects of RAP on concrete properties. Researchers updated his summary table and present it in Table 6. Table 6 shows that adding RAP to concrete causes serious reductions in mechanical properties. Although several different research groups produced RAP concrete with adequate mechanical properties and durability that are qualified by standards (Brand 2012; Berry et al. 2013), how to design concrete containing RAP (especially determining optimum replacement level) with least reduction in performances is considered to be one of the most intractable issues.

Availability, Interest, and Economic Issues for Using RAP in PCC

To investigate the availability of RAP stockpiles in Texas and the level of interest that different districts have for using RAP in PCC, an email survey was sent to 25 districts in Texas for detailed information. The survey results are shown in Appendix B. According to the survey results, 14 out of 25 districts were replied, and only 6 of them showed interests in applying RAP in PCCRAP is commonly accepted as a recycled material added to HMA, bringing considerable savings to various contractors and agents. The feasibility of using RAP in PCC needs to be further investigated from different aspects.

Summary

RAP and RAS are recycled materials that have been widely used in the HMA industry. RAP, produced by milling or crushing old asphalt concrete pavement, typically contains 3 percent to 7 percent of asphalt binder. The gradation of RAP differs depending on the original aggregate gradation and RAP processing procedure. RAP is usually further fractionated to meet the gradation requirement. RAS can be classified as manufacturer waste and tear-off shingles. They are very fine material with asphalt content ranging from 15 percent to 35 percent.

While not too many investigations were completed during the last several decades, there has been a growing interest in the use of RAP in PCC recently. Since 2008, Florida, Illinois, Montana, and Idaho all have completed projects on the topic. Based on the detailed literature review conducted, the addition of RAP in concrete can have following significant impacts on concrete properties:

- According to Table 6, the addition of RAP in PCC generally causes decreases in unit weight, compressive strength, modulus of elasticity, splitting tensile strength and flexural strength. The addition of RAP in PCC generally causes increases in toughness, ductility and porosity. The effects of RAP on PCC's slump, free shrinkage, coefficient of thermal expansion, fatigue properties and rapid chloride permeability are not very clear based on the literature review results.
- The rate of strength loss in tension is lower than that in compression with increasing RAP content. More specifically, the reduction in flexural strength is lower than the corresponding reduction in compressive strength.
- The rate of decrease of MOE is greater than the rate of decrease in strength.

- Though the flexural strength of the concrete made of RAP was lower than that of the conventional concrete, the computed stress to strength ratio for some of the RAP concrete was lower than that for the conventional concrete.
- RAP aggregate may be able to absorb more impact load than virgin aggregate.
- Concrete made of coarse RAP alone shows a better performance in toughness and has the least reduction in strength.
- Failure of RAP concrete in compression often shows failure through the RAP-mortar interface with little aggregate crushing.

Table 6. Published Effects of RAP on Concrete Properties (Updated from Brand 2012).

Concrete Property	Effect on Property as the Amount of RAP in Concrete Increases	References
Air content	Increase	Delwar et al. 1997; Hossiney et al. 2008
	No Effect	Dumitru et al. 1999; Huang et al. 2005, 2006; Hossiney et al. 2010; Bermel 2011
Unit weight	Decrease	Patankar and Williams 1970; Delwar et al. 1997; Hossiney et al. 2008, 2010; Al-Oraimi et al. 2009; Tia et al. 2012
Slump	Increase	Hossiney et al. 2010
	Decrease	Delwar et al. 1997; Huang et al. 2006; Hossiney et al. 2008; Al-Oraimi et al. 2009; Okafor 2010; Tia et al. 2012
	No effect	Bermel 2011
	No clear trend	Huang et al. 2005
Temperature	Increase	Tia et al. 2012
Compressive strength	Decrease	Patankar and Williams 1970; Kolias 1996a; Delwar et al. 1997; Li et al. 1998; 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; Bermel 2011; Bilodeau et al. 2011; Tia et al. 2012; Brand 2012; Berry et al. 2013
MOE	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. 2008, 2010; Al-Oraimi et al. 2009; Bilodeau et al. 2011; Brand 2012; Berry et al. 2013
Poisson's ratio	Increase	Tia et al. 2012
STS	Decrease	Patankar and Williams 1970; Kolias 1996a; Sommer and Bohrn 1998; Dumitru et al. 1999; Mathias et al. 2004; Huang et al. 2005, 2006; Hossiney et al. 2008, 2010; Al-Oraimi et al. 2009; Okafor 2010; Bermel 2011; Tia et al. 2012; Brand 2012
Flexural strength	Decrease	Patankar and Williams 1970; Sommer 1994; Kolias 1996a; Li et al. 1998; Sommer and Bohrn 1998; Dumitru et al. 1999; Hassan et al. 2000; Katsakou and Kolias 2007; Hossiney et al. 2008, 2010; Al-Oraimi et al. 2009; Okafor 2010; Bermel 2011; Tia et al. 2012; Brand 2012; Berry et al. 2013
Direct tensile strength	Decrease	Patankar and Williams 1970; Katsakou and Kolias 2007

Concrete Property	Effect on Property as the Amount of RAP in Concrete Increases	References
Complex stiffness modulus	Decrease	Kolias 1996b; Bilodeau et al. 2011
Resilient modulus	Decrease	Li et al. 1998
Free shrinkage	Increase	Dumitru et al. 1999; Tia et al. 2012
	Decrease	Hossiney et al. 2008
	No effect	Sommer 1994
	No clear trend	Hossiney et al. 2010; Brand 2012
Creep strains	Increase	Kolias 1996a
CoTE	Increase	Tia et al. 2012
	No clear trend	Hossieny et al. 2008, 2010
Toughness	Increase	Huang et al. 2005, 2006; Tia et al. 2012
Fatigue properties	Reduce	Mathias et al. 2004
	Improve	Li et al. 1998
Porosity	Increase	Hassan et al. 2000
Oxygen permeability	Increase	Hassan et al. 2000
Surface absorption	No effect	Al-Oraimi et al. 2009
Frost resistance	Decrease	Sommer 1994; Sommer and Bohrn 1998
Rapid chloride permeability	No effect	Brand 2012
	Increase	Berry et al. 2013
Freeze/thaw resistance	Decrease	Brand 2012; Berry et al. 2013
Abrasion resistance	Decrease	Berry et al. 2013

SCOPES AND OBJECTIVES

Based on the literature review findings, it was decided that this study will mainly focus on portland cement concrete containing coarse RAP because:

- Coarse RAP caused less reduction in concrete mechanical properties based on the results of the previous researches.
- Coarse RAP has lower asphalt content, and asphalt is considered to be detrimental to the modified concrete properties.
- Coarse RAP contains lots of intermediate particles, which is important to obtain dense aggregate gradation (Shilstone 1990).
- The fine RAP is more valuable to HMA industry as it contains rich source of asphalt.

The RAS is likely to have a more significant negative effect on concrete properties. It is not recommended to mix with PCC; as a result, no work on PCC containing RAS is performed in this study because:

- The published researches (Berry et al. 2011; Tia et al. 2012) showed that adding fine RAP caused significant reductions in PCC properties because of a high binder content. The RAS contains even higher amount of asphalt binder than the fine RAP and is expected to cause more significant amounts of reductions to PCC properties.
- The high amount of fine portion in the RAS may absorb extra water in the RAS-PCC system due to its high surface area, which leads to a dry and harsh mix.
- The RAS-PCC is expected to have consolidation problems

For the RAP material selection, the following factors were considered:

- Aggregate types: RAP composed of different stone types is likely to have different effects on concrete performance. Texas has various RAP sources including limestone, gravel, granite, rhyolite, etc.
- Level of interest: 6 out of 14 replied districts showed interests in the use of RAP in PCC; they are Atlanta, San Antonio, Brownwood, Houston, Amarillo, and Bryan. RAP sources from some of these districts are selected in this study.

This study has investigated the applicability of RAP-PCC mixtures for making concrete pavement using locally available non-investigated RAP materials. The objectives of this project are listed below:

1. Full-scale characterization of RAP materials – a detailed characterization of the studied RAP materials and establishing a connection between characterization parameters and RAP PCC performance – this kind of approach has not yet been attempted in any of the published previous studies.
2. Validating the effects of RAP on PCC mechanical properties – no studies have been conducted yet using RAP materials from Texas.
3. Utilization of dense (optimized) combined aggregate gradation and other approaches (e.g., use of ternary blends, fibers and nano-technological applications etc.) to improve RAP-PCC concrete performance - As HMA typically uses dense-graded aggregate with smaller sizes than PCC (the maximum aggregate size for HMA is typically 9.5mm or 12.5mm, while that for PCC can be 25mm or 38mm), the coarse RAP should contain considerable amounts of intermediate size particles (passing 9.5-mm sieve but retained on 2.36-mm sieve) than conventional virgin PCC coarse aggregate. So, replacing certain percentages of virgin coarse aggregate by coarse RAP may lead to producing dense-graded PCC and offer benefits such as (i) making concrete with improved workability and mechanical properties and (ii) reduction in shrinkage and exhibition of equivalent durability performance. Although many investigations regarding concrete containing RAP were conducted around the world in the past, few of them properly utilized the benefits of optimized aggregate gradation in the studied RAP-PCC mixtures.
4. Acquiring better understanding on the durability performance – It is important to identify if there is any durability issues (especially long term durability) related to especially pavement applications.

5. Chemical interaction and hydration behavior due to the presence of asphalt in the PCC system.
6. Application of advanced characterization techniques such as stereomicroscope, X-Ray CT and other suitable micro-analytical techniques to understand crack propagation and other microstructural features and understand the mechanisms of reduction in mechanical properties in RAP PCC system.
7. Developing model to predict pavement performance using RAP-PCC.
8. Perform life-cycle analysis of pavement containing RAP-PCC to evaluate economic, social and environmental effects
9. Develop RAP-PCC design guidelines and recommendations based on the findings of this study.

REPORT ORGANIZATION

Chapter 1 is an introduction includes a detailed literature review on the current topic. The objectives of this research and the report organization are also presented.

Chapter 2 provides a detailed experimental program with comprehensive analysis and discussion of the results covering the use of RAP aggregates to make Class P concrete (concrete paving mixtures) as well as other low strength classes of concrete.

Chapter 3 presents the approaches and findings on RAP-PCC microstructural study and crack propagation through several advanced micro-analytical techniques. These studies help explain the observations obtained in Chapter 2.

Chapter 4 describes the evaluation of PCC pavement containing RAP-PCC material through the application of commercially available performance evaluation model / software. Both mechanical performance and life cycle assessment aspects were evaluated in order to assess the benefits.

Chapter 5 provides the guidelines and implementation recommendations on using RAP in PCC for different civil applications.

Finally, Chapter 6 provides a summary and conclusions based on the research findings from this study.

CHAPTER 2. PROPERTIES OF PCC CONTAINING RAP

In this chapter, a detailed experimental program with comprehensive analysis and discussion of the results covering i) the use of RAP aggregates to make Class P concrete and ii) the use of RAP aggregates to make other low strength classes of concrete (i.e., Class A, Class B, Class C, Class E, Class F, Class H, Class S, and Class SS) is presented.

MATERIALS SELECTION AND CHARACTERIZATION

Since the primary focus of this research was to evaluate the feasibility of using RAP-PCC for pavement applications, all materials used in this research were selected on the basis of producing a typical class P concrete. A conventional TxDOT concrete paving mixture with a commonly used virgin coarse and fine aggregate was considered as a control mix. A typical concrete paving mixture containing #4 coarse aggregate gradation was obtained from a TxDOT construction project. For the cement, a commercially available Type I/II cement made by TXI was used. For the fly ash, a class F fly ash was obtained from Kniferiver Inc., Bryan, Texas. Table 7 lists the chemical compositions of the studied fly ash. A typical mid-range water reducer and an air entraining agent were selected as commonly used chemical admixtures for concrete paving mix. The virgin coarse aggregate was limestone with #4 (#57 in ASTM C 33) gradation specified in the TxDOT standard specifications for construction and maintenance of highways, streets, and bridges (TxDOT 2014). Although the TxDOT standard specifications require the use of #2 or #3 coarse aggregate gradation for concrete pavement, researchers decided to use #4 gradation based on the following reasoning:

- Wanted to reproduce the concrete paving mixture design that was obtained from a TxDOT construction project.
- Local coarse aggregate materials with #4 gradation were easily available.
- There is a little difference between #3 and #4 gradations.
- Most of the published literature on RAP concrete research used #4 gradation, and the use of the same gradation allow the researchers to establish a comparative assessment effectively.

Some selective additional work using concrete made of #3 coarse aggregate gradation is presented in Appendix C. The differences in results between RAP-PCC using #3 and #4 coarse aggregates were found to be negligible. The fine aggregate was a concrete natural siliceous sand with satisfying gradation requirements according to the manual. All the aggregates (both coarse and fine) and admixtures were provided by Kniferiver Inc., Bryan, Texas.

Table 7. Chemical Composition of Fly Ash.

	Class F fly ash
SiO_2	53.46%
Al_2O_3	19.09%
Fe_2O_3	5.98%
MgO	2.92%
SiO_3	0.57%
Na_2O	0.48%
CaO	13.43%

RAP from six sources covering five districts including Houston, Bryan, Amarillo, Childress, and San Antonio were collected. Table 8 lists the tests that were conducted for material characterization for the collected RAP and virgin aggregates. Table 9, Table 10, and Table 11 present the results.

Table 8. Tests to Characterize RAP and Virgin Aggregate Materials.

Test	Standard/Procedure
Specific gravity	ASTM C127, ASTM C128
Absorption	ASTM C127, ASTM C128
Dry rodded unit weight	ASTM C29
Binder content	AASHTO T308
Shape and texture properties	Aggregate Imaging System (AIMS)
Asphalt binder extraction	AASHTO T164
Evaluation of the extracted asphalt grade	Dynamic shear modulus (DSR) test and bending beam rheometer (BBR) test in accordance with the Superpave PG grading system
Identifying minerals present in aggregate	Petrography (ASTM C 295)

Table 9. The Results of Aggregate Materials Characterization.

RAP/ VA Id	Description	Coarse or Fine	Stone Type	Binder Content (%)	Dry Unit Weight	Oven Dry Specific Gravity	Absorption (%)
CA	Virgin coarse aggregate, #4 limestone	Coarse	Limestone with minor chert particles	NA	96.84	2.51	2.79
FA	Virgin fine aggregate, concrete sand	Fine	Siliceous river sand	NA	-	2.58	2.06
HOU_C	Coarse RAP collected from Houston District produced by SCC Asphalt in Houston, TX	Coarse	Gravel made of mostly limestone with some siliceous particles	4.00	83.34	2.41	2.61
BRY_C	Coarse (retained on No. 8 sieve*) RAP collected from Bryan District produced by Kniferiver Inc., Bryan, TX.	Coarse	Limestone with few siliceous particles (minor phase)	6.19	85.69	2.36	1.78
BRY_F	Fine (passing No.8 sieve*) RAP collected from Bryan District produced by Kniferiver Inc., Bryan, TX	Fine	Limestone	8.96	-	2.07	6.87
AMA_C	Coarse RAP collected from Amarillo District produced by J Lee Milligan Inc., Amarillo, TX	Coarse	Mostly siliceous gravel with some limestone particles	5.25	78.36	2.40	1.89
SA_C1	Coarse (1" max size) RAP collected from San Antonio District produced by Dean Word company, New Braunfels, TX	Coarse	Limestone	3.70	91.78	2.43	1.77
SA_C2	Coarse (1/2" max size) RAP collected from San Antonio District produced by Dean Word company, New Braunfels, TX	Coarse	Limestone	4.62	88.98	2.33	2.69
CRS_F	Fine RAP collected from Childress District	Fine	Gravel	6.10	-	2.32	4.07

VA – Virgin Aggregate; * Bryan RAP was a mixture of coarse, intermediate, and fine size particles. A # 8 sieve was used to fractionate the RAP from Bryan District to yield coarse (BRY_C) and fine portions (BRY_F).

Identification of minerals present in the studied aggregates (both virgin and RAP aggregates) was conducted according to the ASTM C295. Thin sections using representative aggregate samples were prepared for all the studied aggregates. The thin sections were investigated using a transmitted light optical microscope (Figure 10) by following the guidelines in ASTM C295. Table 9 includes the results.

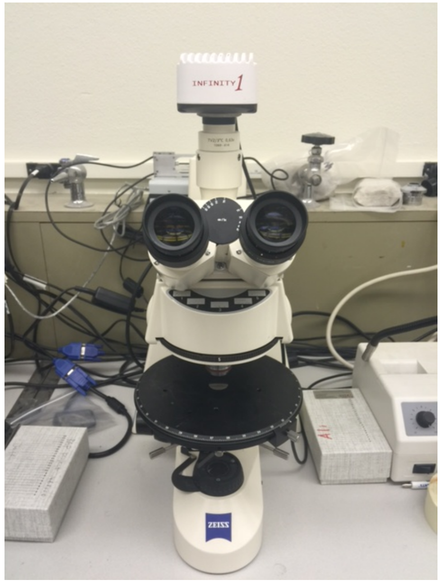


Figure 10. Transmitted Light Optical Microscope.

The Aggregate Imaging System (AIMS) was used to characterize the shape and texture properties of the RAP materials and the virgin coarse aggregate. The equipment uses a variable magnification microscope-camera system and two different lighting configurations to capture aggregate images. With the images, the AIMS software uses a series of algorithms that objectively quantify aggregate shape properties such as angularity, surface texture, sphericity, flat, and elongated distribution (Gates et al. 2011). Figure 11 shows the AIMS.

Table 10 shows the results for HOU_C, BRY_C, AMA_C and SA_C2. Table 10 shows the RAP materials have higher sphericity values and a lower amount of flat and elongation particles, compared to the virgin coarse aggregate. This finding indicates that adding RAP is effective for achieving dense combined aggregate gradation in concrete mixture. According to Richardson (2005), the intermediate particles must be rounded and should not be flat and elongated in order to make an effective dense graded concrete. The SA_C2 is a crushed RAP, so it has the lowest sphericity and the highest flat and elongated distribution. In general, the texture of RAP aggregates is way higher than the texture of CA. The mineralogy of BRY_C and HOU_C is similar to the mineralogy of CA but their texture is totally different. Under an ongoing TxDOT project (0-6921), TTI is investigating this phenomenon. Based on the preliminary results, researchers observed that the texture data from AIMS is very sensitive to the color/shade of the aggregate particles and sometimes can lead to misleading texture values.

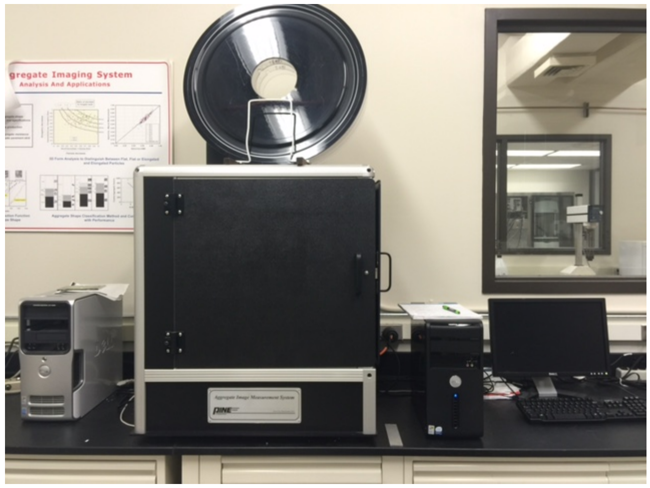


Figure 11. AIMS.

Table 10. AIMS Test Results.

Sample	Size (mm)	Angularity	Texture	Sphericity	Flat and Elongated Distribution (L/S>2:1)	Flat or Elongated Distribution (L/S>2:1)
CA	4.75	2344.4	78.8	0.70	58.9%	17.9%
HOU_C	4.75	2648.6	614.8	0.74	45.0%	13.3%
BRY_C	4.75	2324.6	543.9	0.77	25.0%	6.7%
AMA_C	4.75	2977.0	562.3	0.71	48.3%	5.2%
SA_C2	4.75	2764.9	619.6	0.66	80.0%	30.0%

Aged asphalt binder was extracted from the RAP based on the AASHTO T164 standard. The DSR test and BBR test were performed to re-evaluate the extracted asphalt grade in accordance with the Superpave PG grading system. Figure 12 shows pictures for the DSR machine and the BBR machine. Table 11 lists the test results. AMA_C has more agglomerated particles compared to the other two RAPs. Table 11 indicates that AMA_C is softer, so the particles are easier to form clumps (Figure 13).

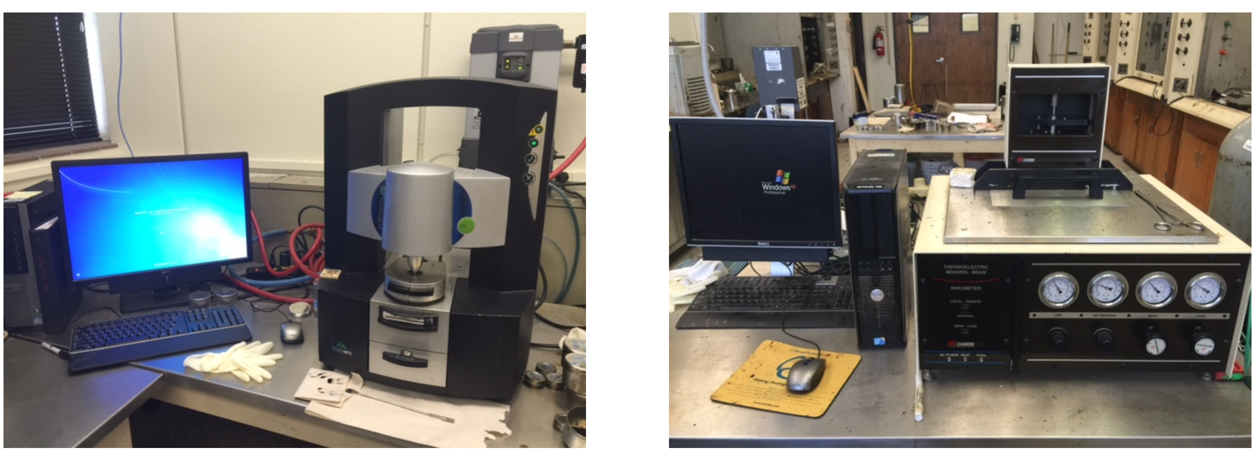


Figure 12. DSR (Left) and BBR (Right).

Table 11. RAP Asphalt Grade Re-Evaluation.

	DSR Result	BBR Result	PG Grade
HOU_C	Passed @82°C, Failed @88°C	Passed @-6°C, Failed @ -12°C	PG 82-16
BRY_C	Passed @82°C, Failed @88°C	Passed @-12°C, Failed @-18°C	PG 82-22
AMA_C	Passed @76°C, Failed @82°C	Passed @-18°C, Failed @-24°C	PG 76-28
SA_C2	Passed @ 88°C, Failed @ 96°C	Passed @ -12°C, Failed @ -18°C	PG 88-22

Figure 13. Agglomerated Particles in AMA_C.

As mentioned in Chapter 1, the strategy in this project was to replace a certain portion of virgin coarse aggregate in concrete mix by RAP with mainly coarse and intermediate size fractions. The inclusion of intermediate size fraction of RAP should facilitate achieving concrete with dense gradation, leading to better workability and improved mechanical properties. Based on the following reasons, researchers decided not to include any fine RAP in this research:

- Based on detailed literature review (Chapter 1), it is widely accepted that adding fine RAP in PCC invariably causes significant reductions of mechanical properties.
- Fine RAP contains higher amount of asphalt, which can be used to make new HMA mix more economically.

Table 12 lists the gradation of the studied coarse RAPs and virgin aggregates (i.e., CA and FA). As can be seen in the table, the HOU_C and AMA_C are RAP sources with high amounts of coarser size fraction. HOU_C and AMA_C happened to have similar gradation with the virgin coarse aggregate. The BRY is an un-fractionated RAP source that contains coarse, intermediate, and fine particles. A No. 8 sieve was used to get rid of the fine portion and accumulate only the coarse and intermediate particles to mix in the concrete (BRY_C). The SA_C2 is also another good source because it is well-graded and contains large amount of intermediate particles but without fine particles. Based on the above gradation information, researchers anticipated that the use of BRY_C and SA_C2 RAPs would facilitate to achieve concrete with near dense aggregate gradation. Selective tests were conducted before conducting the main detailed testing on these RAPs to verify the potential of achieving dense gradation in PCC.

Researchers selected the three coarse RAPs (i.e., HOU_C, BRY_C, and AMA_C) for conducting detailed concrete testing to cover i) RAPs with a wide range of gradation and rock type; ii) RAP materials with a wide range of asphalt binder content.

Some selective tests were also conducted using the coarse RAP SA_C2 in order to verify the benefits of achieving concrete with dense gradation. Figure 14 shows the selected RAPs used in RAP-PCC mixes. Figure 15 presents the gradations of these selected RAPs.

Figure 14. RAP Materials Used in RAP-PCC.

Table 12. Gradation for RAP Materials and Virgin Aggregates.

Sieve	Size (mm)	CA	FA	HOU_C	BRY (C+F)	AMA_C	SA_C1	SA_C2	CRS_F
1 1/2"	38.1	100	100	100	100	100	100	100	100
1"	25.4	99.7	100	100	100	100	99.9	100	100
3/4"	19	81	100	82	100	78	94	100	91
1/2"	12.5	42	100	38	90	44	78	99.9	85
3/8"	9.5	19	100	9	73	18	67	77	77
No. 4	4.75	5	96	2	42	4	39	12	49
No. 8	2.36	3	85	2	22	1	21	0	31
No. 16	1.18	0	74	0	9	0	14	0	21
No. 30	0.6	0	60	0	3	0	9	0	13
No. 50	0.3	0	15	0	1	0	8	0	5
No. 100	0.15	0	2	0	1	0	0	0	1
No. 200	0.075	0	0	0	1	0	0	0	0
Pan	0	0	0	0	0	0	0	0	0

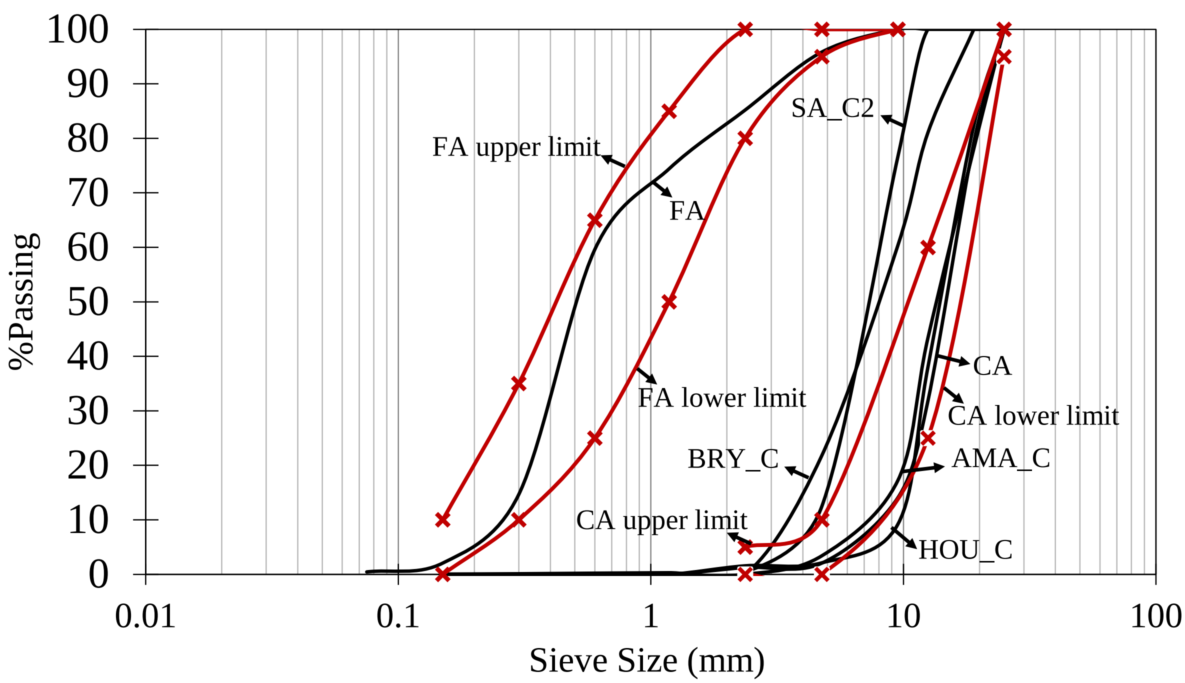


Figure 15. Gradation for the Selected RAPs.

USE OF RAP TO MAKE CLASS P CONCRETE

The class P concrete mix design development with specific details on attaining optimized aggregate gradation due to the replacement of virgin aggregate by RAP aggregates is provided below.

Mix Design and Optimized Aggregate Gradation

A series of trial mixes with 0.45 water/cementitious (w/cm) ratio and 656 lb/cy cementitious content was initially designed because the researchers intended to use high w/cm and cementitious content to compensate the low workability and low strength of RAP concrete, which was commonly reported from previously published literatures. After a thorough assessment of the trial mixes (presented in Appendix D), researchers made a decision to reduce the w/cm to 0.40 and to decrease the cementitious content to 520 lb/cy for the mixes used for the detailed testing, because:

- In general, the slump values of the trial mixes were very high, causing potential segregation issues.
- The cementitious content of 656 lb/cubic yard is higher than the common practice for the typical Class P concrete in Texas (The common practice for TxDOT Class P mix is to use a cememtitious content that does not exceed 520 lb/cy; a written approval needs to be obtained if the cementitious material exceeds 520 lb/cy. The cementitious content can not exceed 700 lb/cy).

Based on the hardened concrete properties results from the trial mixes, coarse RAP replacements up to 40 percent (depending on the type and quality of RAP) can practically be allowed with permissible reduction of different mechanical properties (e.g., different strengths) in comparison with the reference concrete. Any higher amount (greater than 40 percent) led to significant reduction (more than permissible limit) in mechanical properties in comparison with the reference concrete, which might not be acceptable from a practical standpoint. As a result, the virgin coarse aggregate was replaced up to 40 percent by the selected RAPs (i.e., HOU_C, BRY_C, and AMA_C) in the detailed testing plan. The mix ID in this project was assigned with the following format:

w/cm_cementitious content_replacement level+RAP type

Example: 0.40_520_40HOU represents a mix that has 0.40 w/cm ratio, 520 lb/cy cementitious content, and HOU RAP to replace 40 percent of virgin coarse aggregate. Table 13 presents the mix design for the 0.40_520 PCC mixes.

Table 13. Mix Designs for the 0.40_520 Mixes.

	0.40_520_REF	0.40_520_20 HOU	0.40_520_40 HOU	0.40_520_20 BRY	0.40_520_40 BRY	0.40_520_20 AMA	0.40_520_40 AMA	0.40_520_30 BRY*	0.40_520_35 SA*
Cement (lb/cy)	416	416	416	416	416	416	416	416	416
Fly Ash (lb/cy)	104	104	104	104	104	104	104	104	104
Virgin coarse aggregate (lb/cy)	1783	1391	1018	1399	1030	1419	1058	1237	1160
RAP (lb/cy)	0	348	679	350	687	340	675	499	580
FA (lb/cy)	1296	1326	1356	1308	1320	1306	1316	1312	1295
Water Reducer (fl oz/cy)	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4
Air Entraining Agent (fl oz/cy)	1.563	1.563	1.563	1.563	1.563	1.563	1.563	1.563	1.563
Water (lb/cy)	208	208	208	208	208	208	208	208	208

* The mechanical properties were tested for the 0.40_520_30BRY and the 0.40_520_35SA mixtures in order to validate the strengths and asphalt fraction relationship (presented later)

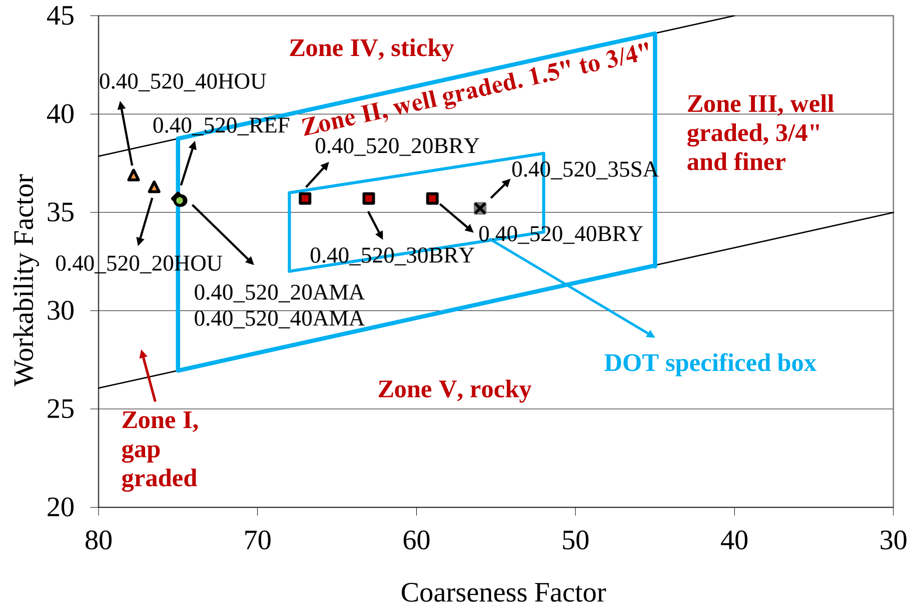
The Effect of RAP Gradation on Concrete Combined Aggregate Gradation

Based on the previously reported research, replacing virgin aggregate (≤40 percent) by suitable RAP aggregate provides a benefit of achieving dense combined aggregate gradation. This is because HMA typically uses smaller aggregates than PCC, which makes RAP a rich source of intermediate particles, and the intermediate particles are what a conventional concrete mix lacks. Shilstone (Shilstone 1990) initiated a dense gradation mix design (reviewed in Appendix A). TxDOT adopted this method and formulated the designation Tex-470-A. Using the form 2227, the optimized aggregate gradation analysis was conducted for various RAP concrete mix designs (Table 13). Figure 16(a) shows the CF chart. As can be seen in Figure 16(a), because the HOU_C and AMA_C have similar gradations with the virgin coarse aggregate, replacing the virgin coarse aggregate with either of them does not change the combined gradation very much. So, the 0.4_520_HOU series, the 0.4_520_AMA series, and the 0.4_520_REF are close to each other (close to the border between well-graded region and coarse gap-graded region). The combined gradations of the 0.4_520_BRY mixes (i.e., 20, 30, and 40 percent replacements) fall within the workability box (30 and 40 percent mixes lie almost at the middle), indicating that the 0.4_520_BRY mixes can be considered as dense graded PCC mixes. Since the dense gradation is beneficial for concrete workability and mechanical properties, the 0.4_520_BRY was anticipated to have better performance in terms of better workability and improved mechanical properties in comparison with control mixes. The 0.4_520_35SA mix is also qualified as a dense graded PCC mix. The previous research indicated that the concrete mix with 40 percent RAP showed the best gradation as well.

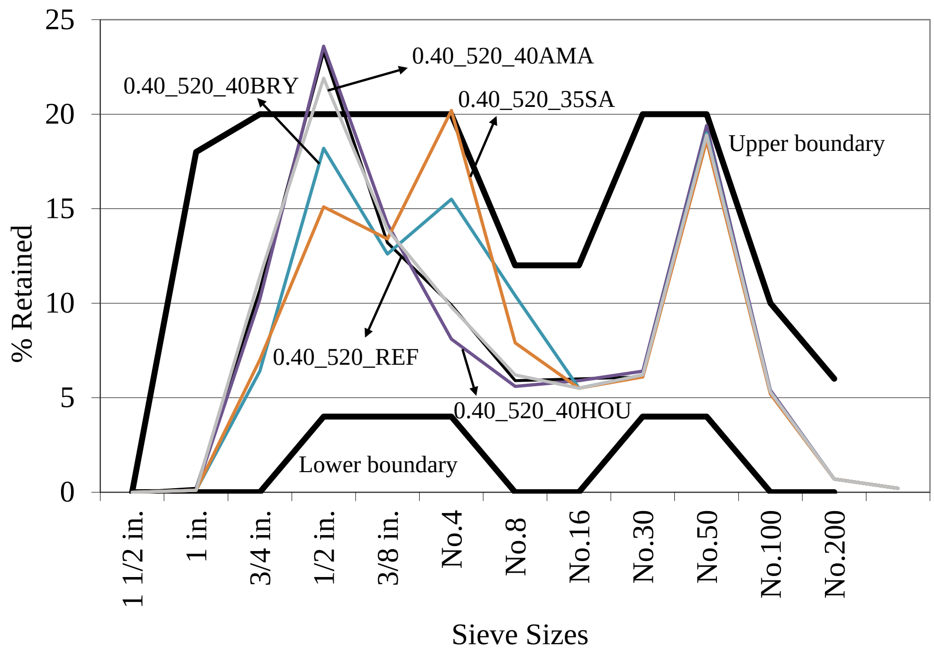
In the newly published Tex-470-A designation, the optimized aggregate gradation is evaluated through the percent retained chart. The combined percent retained gradations must meet the following criteria:

- It must be within the upper and lower boundaries.
- The sum of the percent retained on the No. 8 sieve to the No. 30 sieve must not be less than 15 percent.
- The sum of the percent retained on the No. 30 sieve to the No. 200 sieve must be between 24 percent and 34 percent.

Figure 16(b) plots the percent retained charts for various RAP concrete mixes in this project. The chart indicates the 0.40_520_40BRY, the 0.40_520_30BRY, and the 0.40_520_35SA mixes can meet the requirements, while the other mixes all have a peak at 1/2 in. sieve, which is out of the upper limit.



(a) CF chart



(b) Combined percent retained chart

Figure 16. Optimized Aggregate Gradation Analysis.

Ideal RAP Gradation

The studied RAPs were obtained directly from the HMA making plants, so their gradations followed the requirements for producing HMA. It has been shown in Figure 16 that some RAP gradations yielded dense-graded RAP-PCC mixtures while the other could not. Therefore, it is crucial to make RAP stockpiles with suitable gradation in order to facilitate making RAP-PCC mixtures with optimized aggregate gradation. In order to find an ideal RAP gradation corresponding to different RAP replacement levels, a Matlab code was developed. The ideal RAP gradation was determined so that the combined gradation yielded a position location that was closest to the middle point (CF=60, WF=35) of the workability box in the CF chart. Since the CF and WF calculation only requires the percentage passing values for 3/8 in. sieve and No. 8 sieve, no requirement is needed for the other sieves sizes in the ideal RAP gradation by the CF chart. Table 14 tabulates a summary of the ideal RAP gradation for the various RAP replacement levels.

Table 14. Ideal RAP Gradations Required by the CF Chart.

Replacement Level	% Passing 3/8" Sieve	% Passing No. 8 Sieve	Corresponding CF	Corresponding WF
20%	100	0	60.14	36.45
25%	81	0	60.05	36.20
30%	71	0	60.02	35.67
35%	63	0	59.89	36.42
40%	58	0	59.84	35.67

After the computation of the percentage passing values for 3/8 in. and percent No. 8 sieve, the percentage passing values for the other sieve sizes can be determined in accordance with the TxDOT requirements by the combined percent retained chart. This calculation led to multiple solutions. Table 15 lists examples of the ideal gradations for the corresponding RAP replacement level.

Table 15. Examples of the Ideal RAP Gradations (Percent Passing Each Sieve).

Replacement Level	20%	25%	30%	35%	40%
1"	100	100	100	100	100
3/4"	100	100	100	100	100
1/2"	100	100	100	100	100
3/8"	100	81	71	63	58
No. 4	50	40	35	30	20
No. 8	0	0	0	0	0
No. 16	0	0	0	0	0
No. 30	0	0	0	0	0
No. 50	0	0	0	0	0
No. 100	0	0	0	0	0
No. 200	0	0	0	0	0
Pan	0	0	0	0	0

Figure 17 plots the ideal gradations and the RAP gradation together. In Figure 17, BRY_C and SA_C2 are close to the ideal gradation curves of 30-40% replacement levels, indicating these two RAP gradations can produce dense aggregate gradation when the corresponding RAP replacement level is applied. For the HOU_C and AMA_C, they are too far away from these ideal gradation curves, so they could not yield dense gradations. These conclusions match the results from the CF chart analysis (Figure 16).

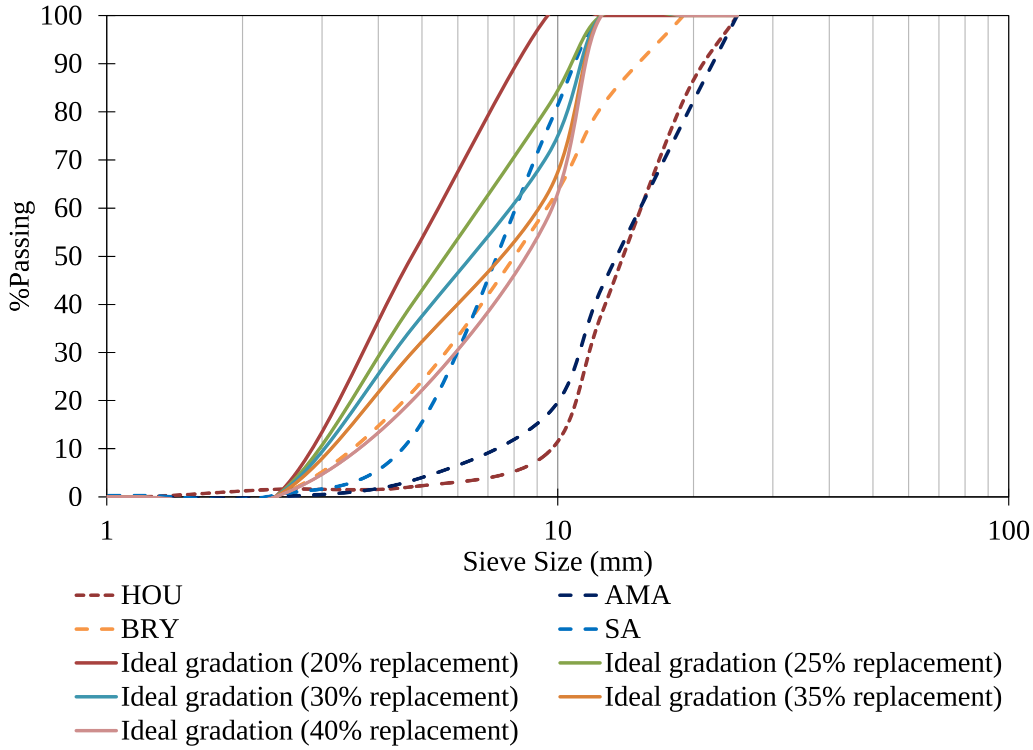


Figure 17. Comparison among Ideal Gradations and Tested RAP Gradations.

It has to be noted that the ideal gradation determined in this section was on the basis of the specific mix design for this project using 0.40 w/cm ratio, 520 lb/cy cementitous content, #4 coarse limestone and the concrete sand. If the mix design changes, the ideal RAP gradation will also change. However, with the code developed in this project, the ideal RAP gradations for different mix designs can be easily obtained.

Mechanical Properties Tests

The production of RAP-PCC was in accordance with the normal practice of making conventional concrete samples. Before mixing, all the aggregate and RAP materials were oven-dried and the moisture was compensated in the mix design based on their absorption capacity. A 9 ft^3 steel mixer and a 4 ft^3 plastic mixer were used in combination. The RAP concrete mixing procedure (Table 16) was developed based on standard concrete mixing practice in the lab. During the mixing and casting of RAP-PCC, no abnormal observations were recorded.

Table 16. RAP Concrete Mixing Procedures.

Step	Description
1	Batch all the ingredients
2	Batch the mixing water and add the water reducer and the air entraining agent into it
3	Place all of the coarse aggregates and the RAPs in the mixer
4	Mix 1 minute and let RAP distribute uniformly in the mixer
5	Add 1/3 of the prepared mixing water and mix for 30 seconds
6	Dump all the fine aggregate and the cementitious materials in the mixer, and add the rest of the mixing water and mix for 3 minutes
7	Stop mixing and let the concrete rest for 2 minutes
8	Mix 3 more minutes
9	Pour the concrete into the cart and carefully scrape out the cement paste and the cement mortar attached to the mixer

Fresh Concrete Properties

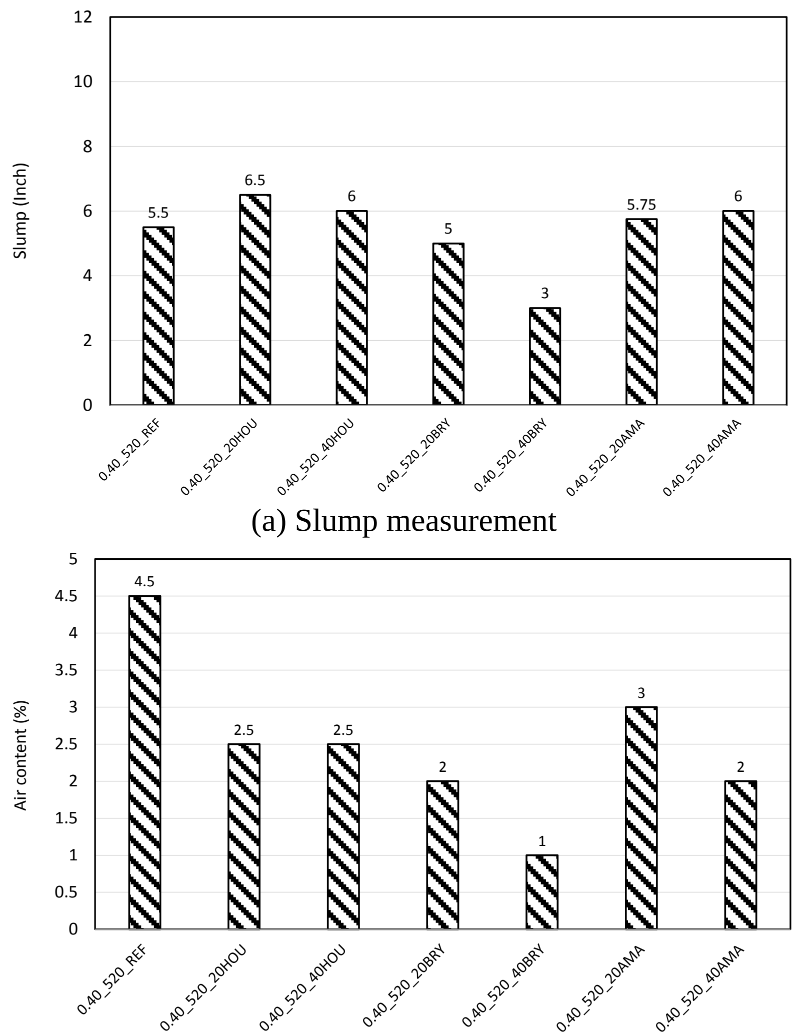
Immediately after finishing mixing, the tests (Table 17) to determine fresh concrete properties were performed.

Table 17. Test Methods to Determine Fresh Concrete Properties.

Test	Standard
Slump	ASTM C 143
Air content	ASTM C 173

Fresh Concrete Properties Test Results

The results of fresh concrete properties for the 0.40_520 series are presented. The slump test result in Figure 18(a) shows that the addition of HOU_C or AMA_C slightly increased the slump, while adding BRY_C reduced the slump of the mix. Despite of lower slump values, the 0.40_520_BRY mixes showed the best workability performances (i.e., the concrete was very flowable, uniform [no segregation], and workable). Researchers observed earlier that 0.40_520_BRY mixes fell inside the box of the workability chart (Figure 16), which indicates that adding Bryan RAP helps to achieve dense combined aggregate gradation. The flowability of any dense graded concrete mix is better than the conventional gap graded concrete mix. Moreover, higher asphalt content of the Bryan RAPs may have created RAP particles with higher smoothness, which also facilitates better flowability. It seems the water demand for 0.40_520_BRY mixes in order to have slump of around 6 in. may be higher (because of higher surface area) than the other RAP mixes with gap combined gradation. In terms of air content, all the RAP concrete samples showed lower air contents than the reference sample (Figure 18(b)).



(a) Slump measurement

(b) Air content measurement

Figure 18. Fresh Properties of 0.40_520_HOU Mixes.

Hardened Concrete Properties

Table 18 lists the hardened concrete properties that were determined. The specimens of varying dimensions required to determine different hardened properties were cast. The molded specimens were placed inside a room with temperature at 25°C for initial curing. After 24 hours, all the specimens were demolded and then transported to a moist curing room.

Table 18. Test Methods to Determine Hardened Concrete Properties.

Test	Sample Size	Curing Age
Compressive strength (Tex-418-A)	4"× 8" cylinder	7-day, 28-day, 56-day*
MOE (ASTM C469)	4"×8" cylinder	
Flexural strength (TEX-448-A)	6"× 6"× 20" beam	
STS (ASTM C496)	4"× 8" cylinder	
CoTE (AASHTO T336)	4"× 8" cylinder	28 days
Poisson's ratio (ASTM C469)	6"× 12" cylinder	
Thermal properties (Hot disk)	4"× 2" disk	

*The RAP-PCC made with AMA RAP showed higher strength reductions than the other RAP-PCC samples. Only 7-day and 28-day mechanical properties tests were conducted for the RAP-PCC made with AMA RAP. No other testing such as CoTE, Poisson's ratio and thermal properties and durability tests were performed on the AMA RAP-PCC.

Compressive Strength

Compressive strength is the most commonly used parameter to characterize concrete property. It can be directly correlated with other concrete properties such as elastic modulus, MOR, and STS. Tex-418-A specifies this test and the researchers strictly followed this testing procedure in this project. A MTS machine, which has a 230 kips capacity, was used in the test. The test was performed at a controlled force mode (440 lb/sec). Researchers prepared 4 in. × 8 in. cylinders, and the specimens were tested at curing ages of 7 days, 28 days, and 56 days, respectively. Figure 19 shows a picture of the compressive strength test.

Figure 19. Compressive Strength Test.

MOE and Poisson's Ratio

MOE and Poisson's ratio are another two important material properties for concrete. Both of the tests were conducted in accordance with ASTM C469, but they were conducted separately. The MOE test was performed using the 4 in. × 8 in. cylinders with the 230-kip MTS machine at a constant displacement rate of 0.0008 in./sec while the Poisson's ratio test was conducted on the 6 in. × 12 in. cylinders via a 400-kip Tinius Olsen machine at a constant displacement rate of 0.05 in./min. For the MOE test, a ring attachment was used to hold two axial linear variable differential transformers (LVDTs), while the attachment for the Poisson's ratio test was equipped with three radial LVDTs and three axial LVDTs. The MOE tests were conducted at sample curing age of 7, 28, and 56 days, while the Poisson's ratio measurement was only made on the specimens after a 28-day moisture curing. Figure 20 shows a picture of the MOE test.

Figure 20. MOE Test.

Flexural Strength/MOR

Concrete is a material that is strong in compression but weak in tension. The characterization of concrete tensile property is of great importance because it determines crack initiation and propagation. The uniaxial direct tension test is the ideal test to evaluate concrete tensile property. However, such test is extremely hard to perform because of the brittle nature of cementitious concrete material. Therefore, flexural strength is widely used to indicate the tensile property of concrete in an indirect way. In this project, a simple beam with third-point loading method was adopted and the flexural test was conducted in accordance with Tex-448-A. The test machine was a MTS machine with 20 kips loading capacity. The flexural beams that had dimension of 6 in. × 6 in. × 20 in. were tested at 7, 28, and 56 days of moist curing. Figure 21 shows a picture of the flexural strength test.

Figure 21. Flexural Strength Test.

STS

Like the flexural test, STS is another indirect measurement of concrete tensile strength. One benefit of the STS test over the flexural test is that it can be performed on 4 in. × 8 in. cylinders, which saves a significant amount of material and labor for sample preparation. In this project, this test was conducted followed by ASTM C496 using the 230 kips MTS machine at 7, 28, and 56 days of concrete curing age. Figure 22 shows a picture of the STS test.

Figure 22. STS Test.

CoTE

The CoTE will largely affect the pavement's expansion and contraction characteristic. It is also an input for predicting slab curling and wrapping. The measurements made in this project were in accordance with AASHTO T336. Three sample duplicates that had been cured for 28 days were tested for each type of mix. Figure 23 shows a picture of the CoTE test.

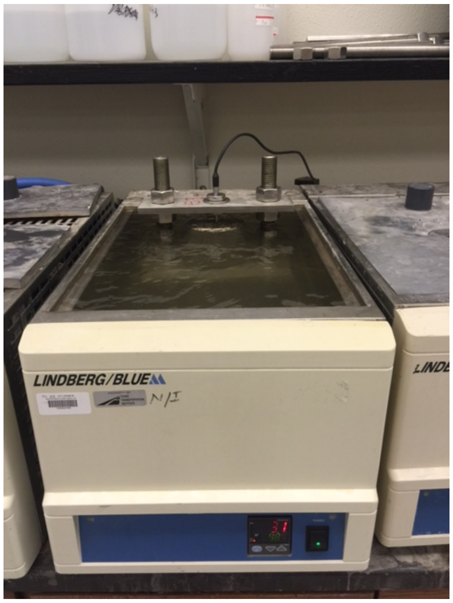


Figure 23. CoTE Test.

Thermal Properties

Concrete thermal properties control the heat transfer within the pavement structure. Thermal conductivity measures the how fast a material conducts heat, and heat capacity quantifies the amount of heat needed to raise material temperature. Both of them are important inputs in the mechanistic-empirical pavement design guide (MEPDG) for calculating pavement thermal stress. In this project, the thermal properties of RAP-PCC were measured using Hot Disk TPS 2500S device (Figure 24). The testing procedures were based on researchers' previous experience (Shi 2014; Shi et al. 2015): The concrete samples were cut into several disks, and the TPS 2500S sensor was sandwiched by the disk samples to make measurements (Figure 25). The thermal properties of the 0.40_520 mixes at 28 days were tested.

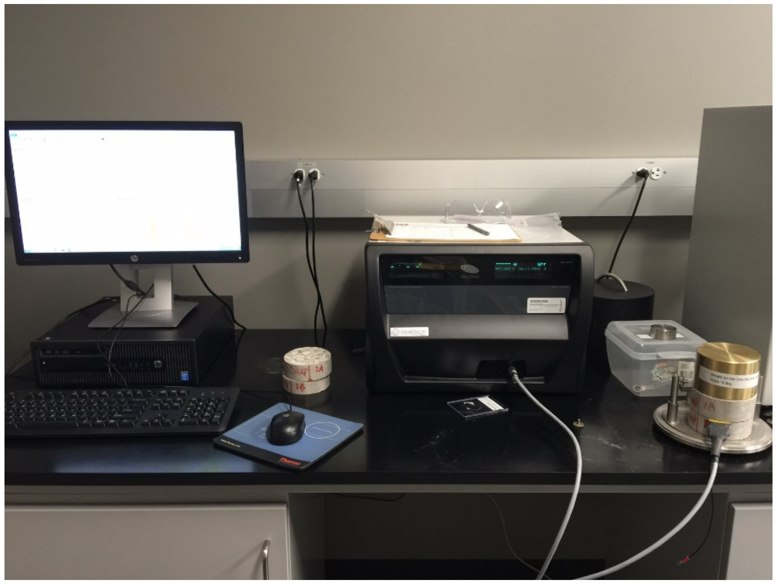


Figure 24. Thermal Properties Tests.

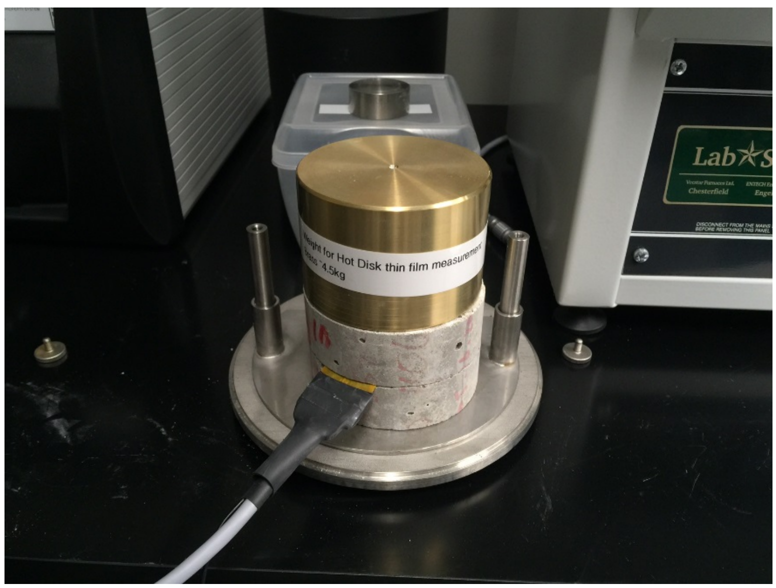
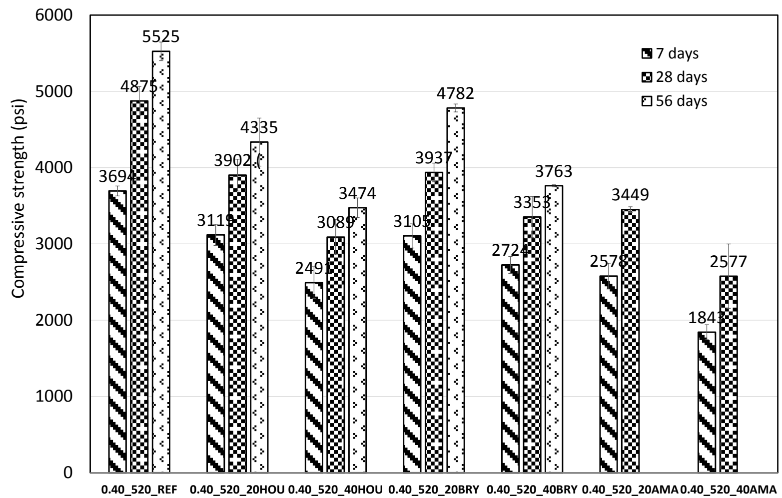


Figure 25. Thermal Properties Test Set-Up.

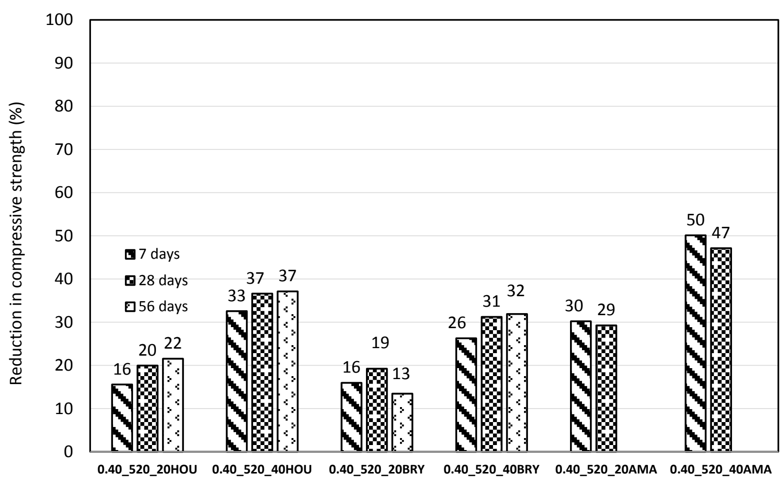
Hardened Concrete Properties Test Results

Compressive Strength

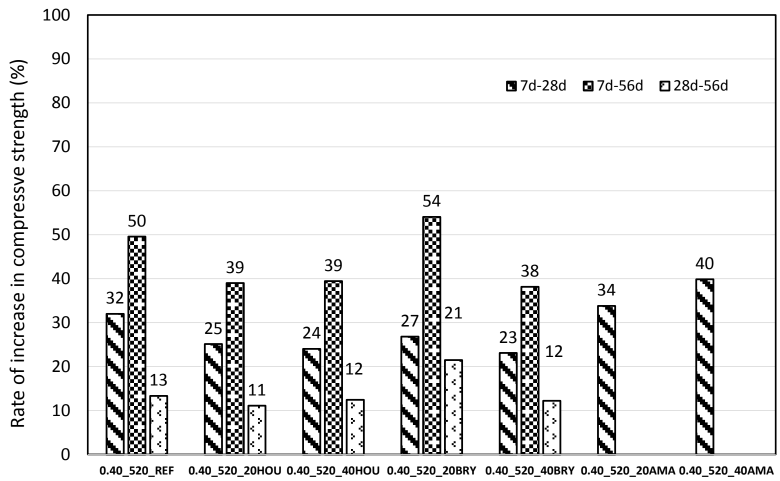
Figure 26 presents the absolute values of CS, the percentage reduction of CS in comparison with to the reference mix, and the rate of increase of CS over time. The results show that replacing virgin aggregate with BRY_C had the least reduction in compressive strength, followed by HOU_C and AMA_C. Since the mineralogy of HOU_C and BRY_C stones are similar (majorly limestone), the main reason that the concrete containing BRY_C had higher strength is considered due to the dense gradation. The AMA RAP concrete had much more significant strength reduction compared the HOU RAP concrete and BRY RAP concrete, which was likely due to the high amount of agglomerated particles in the mix. This is also supported by the broken specimen after testing in Figure 27. Figure 27 clearly shows there were agglomerated particles in the broken cross section. Moreover, the AMA RAP contains mainly siliceous particles. The rate of increase of CS over time (i.e., 7-28 and 7-56 days) for the RAP concrete mixes (irrespective of the type of RAPs) is in general lower than the control mixes. However, the rate of increase of CS from 28 to 56 days is comparable for both RAP and control mixes. Interestingly, the rate of increase of CS from 28–56 and 7–56 days for 0.4_520_BRY mixes are higher than that at control mix.



(a) Compressive strength



(b) Percentage reduction in comparison with the reference mix



(c) Rate of increase over different time intervals

Figure 26. Compressive Strength Results for 0.40_520 Mixes.

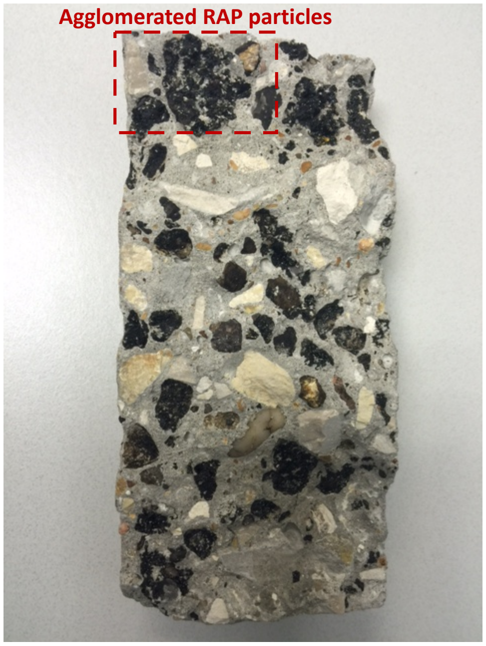
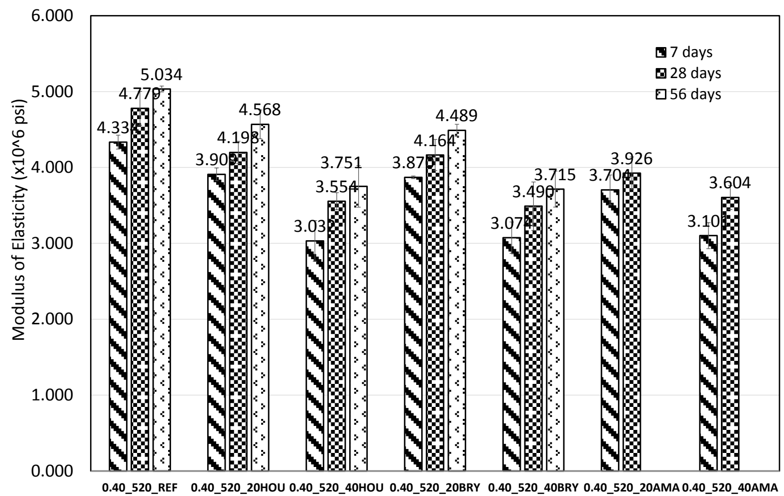


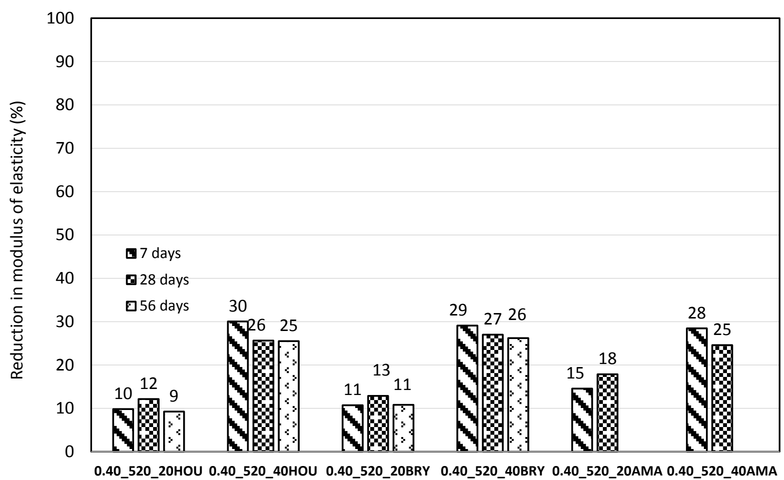
Figure 27. Agglomerated RAP Particles from a Cross Section View of 0.40_520_40AMA.

MOE and Poisson's Ratio

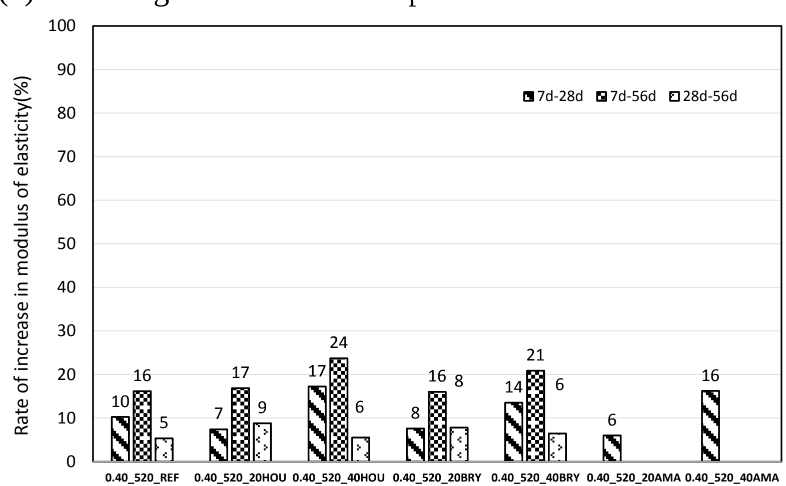
Figure 28 shows the MOE results, which suggest that all three different types of RAP concrete mixes had similar level of reduction in MOE. The 0.4_520_20AMA samples had a slightly higher reduction than other RAP concrete mixes. Figure 28(c) shows that the samples for the 20 percent replacement level had similar rates of increase over time while the samples for the 40 percent replacement level tended to have higher rates, compared to the reference mix.



(a) MOE



(b) Percentage reduction in comparison with the reference mix



(c) Rate of increase over different time intervals

Figure 28. MOE Results for 0.40_520 Mixes.

Figure 29 plots the Poisson's ratios for 0.4_520_HOU and 0.4_520_BRY mixes at 28 days moist curing. The results indicate that adding RAP into the concrete mix would increase the Poisson's ratio slightly.

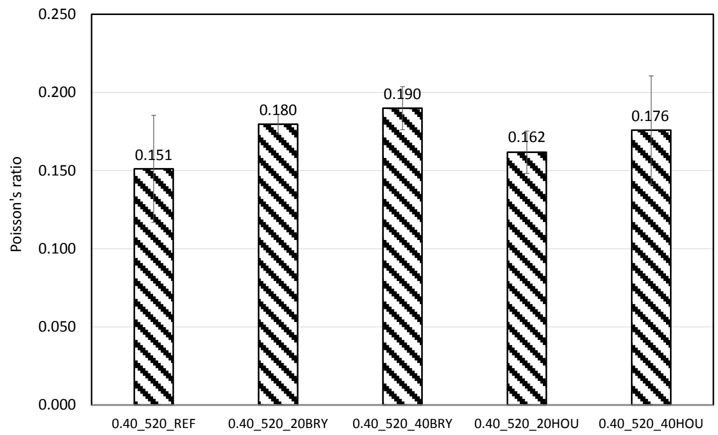


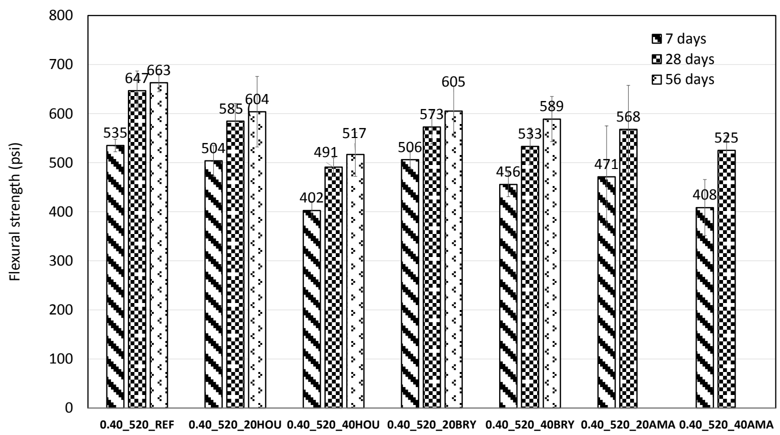
Figure 29. Poisson's Ratio for 0.40_520 Mixes.

Flexural Strength

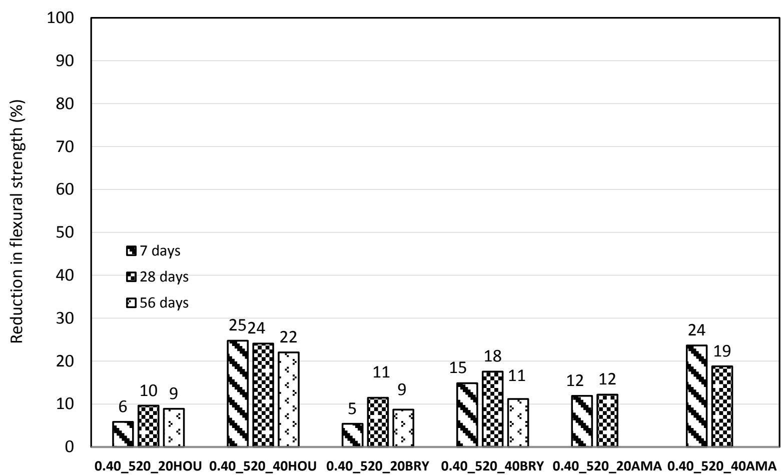
Figure 30 plots the absolute values of MOR, the percentage reduction of MOR in comparison with the reference mix, and the rate of increase of MOR over time. Based on the results obtained, the important observations are listed below.

At 20 percent replacement level, both BRY and HOU RAP mixes show lower percentage of reduction than the AMA RAP mixes. However, at 40 percent replacement level, the BRY RAP mixes show lowest percentage reduction of MOR than the other two RAP mixes (Figure 30(b)). The percentage reduction of the compressive strength (Figure 30(b)) is much higher than the percentage reduction of the MOR. For the replacement level of 40 percent, the BRY RAP concrete yielded obviously better result than the other two types of RAP concrete mixes. This is mainly due to the dense combined aggregate gradation of concrete containing BRY RAP. Interestingly enough, although the AMA RAP concrete showed much higher reduction in compressive strength (Figure 28(b)), its rate of reduction level in flexural strength was close to the HOU RAP concrete (Figure 30(b)). These findings suggest that the aggregate gradation may play an important role in determining flexural strength behavior of the RAP-PCC mixes, while aggregate quality may have greater influence on compressive strength behavior.

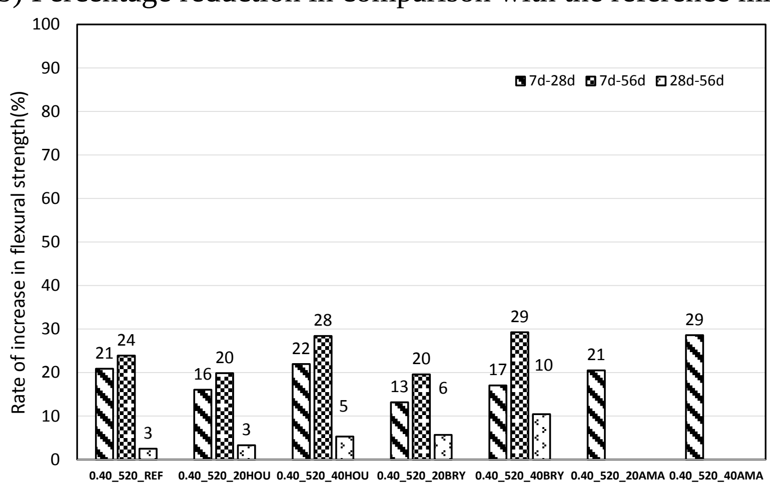
The samples of 40 percent RAP replacement level showed a higher rate of increase over time compared to the samples of 20 percent RAP replacement level. The rate of increase of MOR for the mixes with 40 percent RAP replacement is higher than that at control mix. However, the rate of increase of MOR for the mixes with 20 percent RAP replacement is either little lower or comparable with the control mix.



(a) Flexural strength



(b) Percentage reduction in comparison with the reference mix

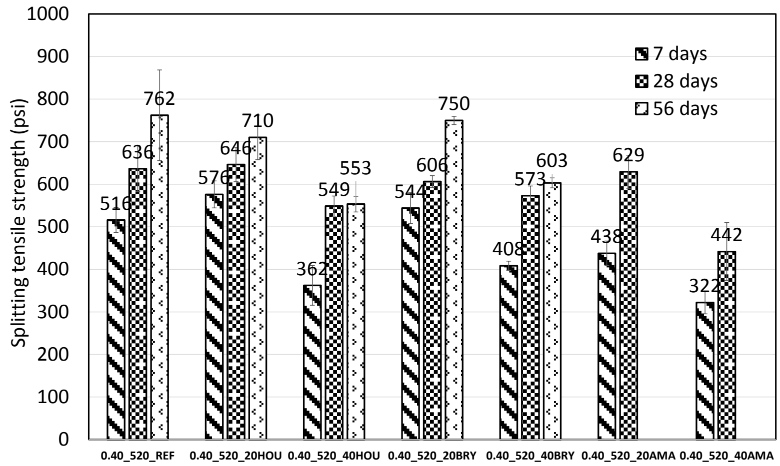


(c) Rate of increase over time

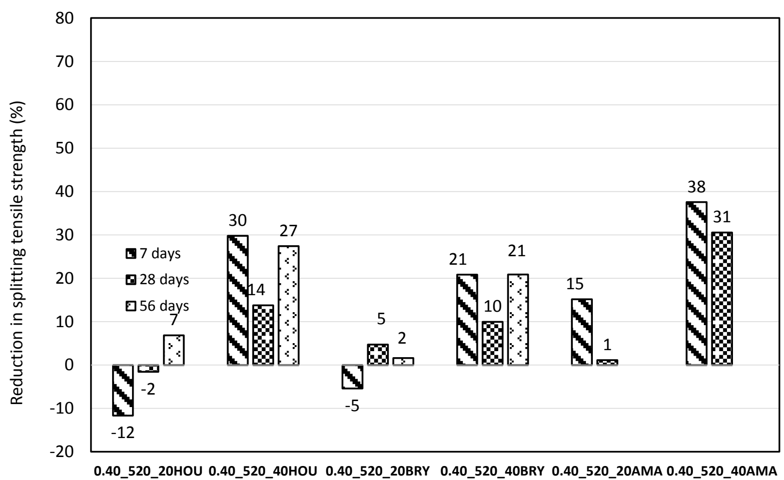
Figure 30. Flexural Strength Results for 0.40_520 Mixes.

STS

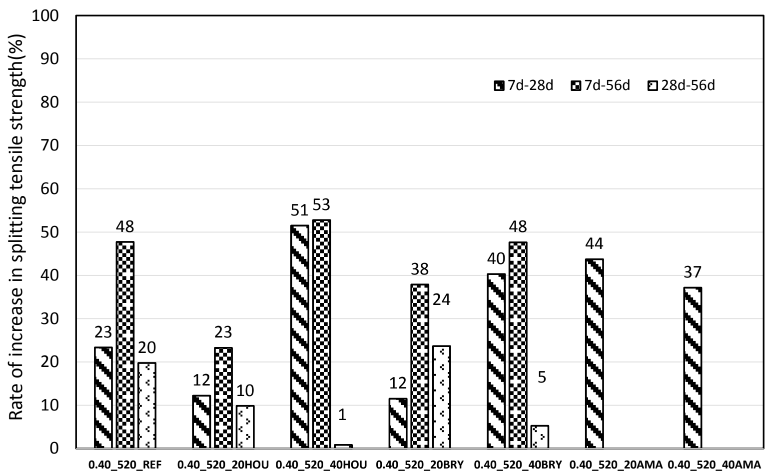
Figure 31 presents the results for the STS of the concrete containing RAP. For the 20 percent replacement level, the strength reduction was small; both of the HOU RAP concrete and the BRY RAP concrete samples even had increased STS compared with the reference mixes. When 40 percent of RAP was added, the reduction became obvious. The BRY RAP concrete yielded the highest STS, followed by the HOU RAP concrete and the AMA RAP concrete.



(a) STS



(b) Percentage reduction in comparison with the reference mix



(c) Rate of increase over different time intervals

Figure 31. STS Results for 0.40_520 Mixes.

CoTE

Figure 32 compares the CoTE results for 0.40_520_HOU mixes and 0.40_520_BRY mixes. All of the results are within the normal range of the value for typical PCC. However, all the RAP concrete samples showed relatively higher CoTE than the reference samples. The higher the amount of RAP in the mix, the higher the CoTE is. The virgin coarse aggregate and BRY RAPs are made of limestone particles. The HOU RAP primarily contains limestone with some siliceous particles. Therefore, the change of CoTE is mainly controlled by the binder content of the RAP used to make concrete. With increasing RAP content in the mix, the total binder content of the mix increased, which resulted in higher CoTE because the binder has a higher CoTE than the main limestone coarse aggregate in this case.

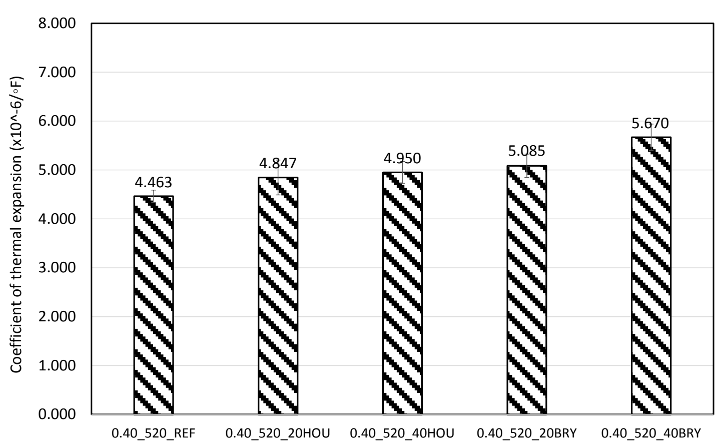
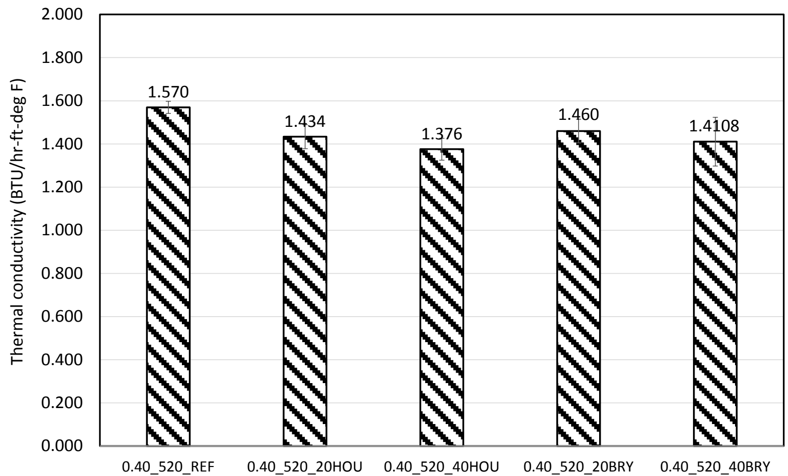


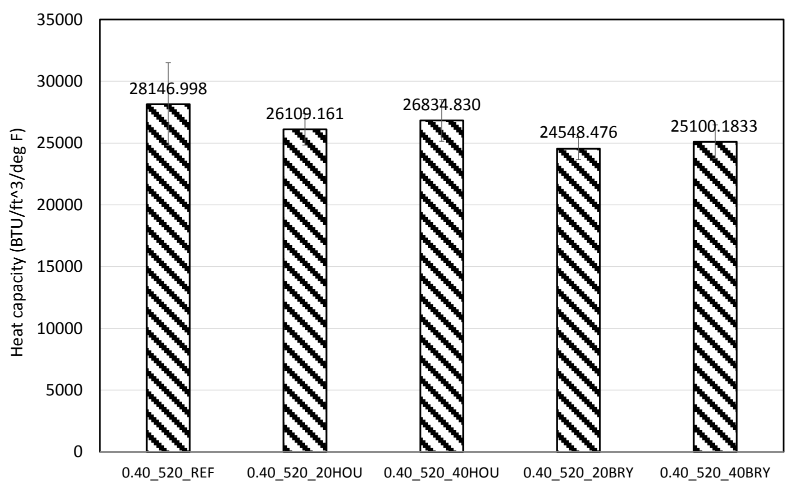
Figure 32. CoTE for 0.40_520 Mixes.

Thermal Properties

The thermal conductivity and the heat capacity of the 0.40_520 mixes were tested. For each type of material, four disk samples were made so that three data points were obtained. Figure 33 shows the averaged results. From Figure 33(a), the thermal conductivity of RAP-PCC samples was lower than the plain PCC sample, which makes sense because the asphalt itself is more insulating. Figure 33(b) shows that adding RAP into PCC reduced the heat capacity.



(a) Thermal conductivity



(b) Heat capacity

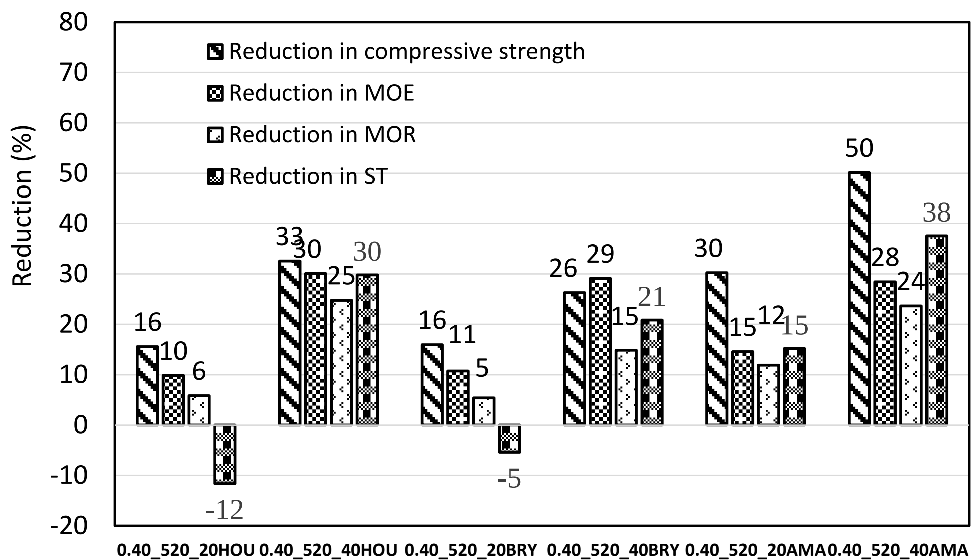
Figure 33. Thermal Properties for 0.40_520 Mixes.

Analysis and Discussion of Mechanical Properties Test Results

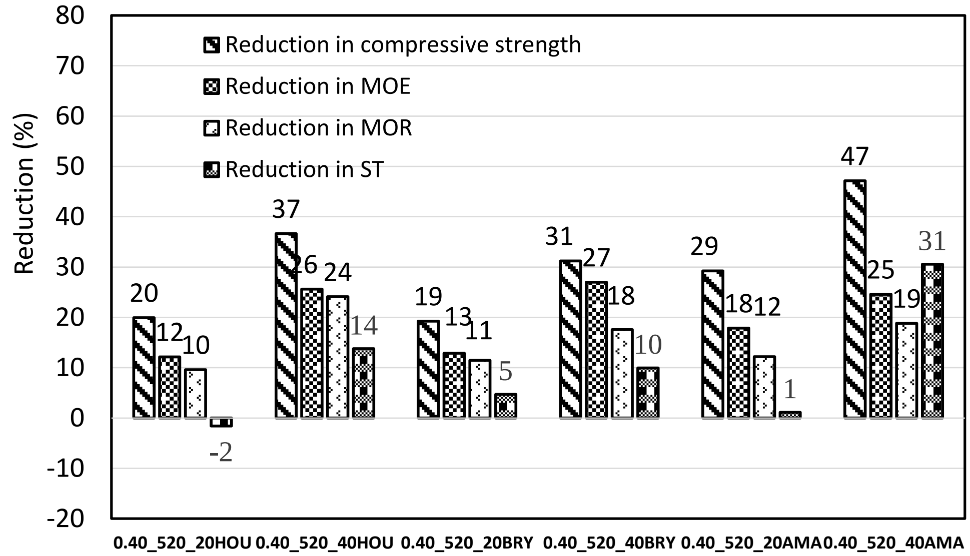
The analysis and discussion of the concrete test results with sufficient details are presented below.

Comparison between Different Properties

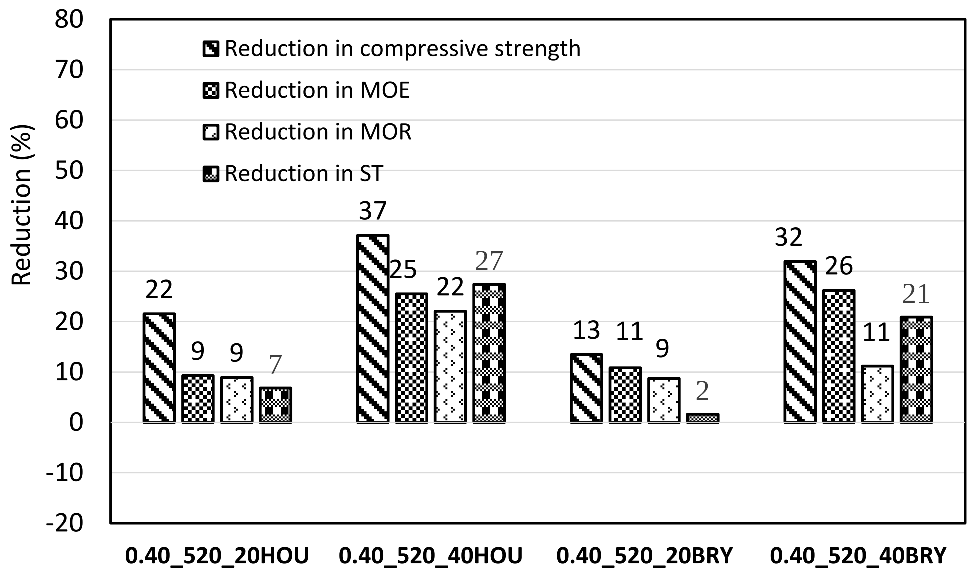
Figure 34 compares the percentage reduction in different mechanical properties for various 0.40_520 RAP concrete mixes. For the most cases, the compressive strength of concrete was the parameter that had the highest rate of reduction. When the RAP replacement level reached a high level (40 percent), the trend became clearer: the rate of reduction followed the sequence of the compressive strength, STS, MOE, and the flexural strength, from high to low. In general, 0.40_520_BRY mixes show lower percentage reduction of mechanical properties than the RAP mixes made of both HOU and AMA RAPs (more prominent with 40 percent replacement level than 20 percent replacement). The AMA RAP mixes show the highest reduction. Interestingly enough, the results showed the inclusion of small amounts of RAP could possibly improve the concrete's splitting tensile strength, and this phenomenon occurred more frequently in the earlier age of the RAP-PCC, This is because at the early age of RAP-PCC, the cement paste has not gain sufficient strength (especially tensile strength) and is vulnerable to cracking, so adding RAP into the system may have little effect on composite strength. When the cement paste turns much stronger at 28-day, the asphalt-cement interfaces behave as weak zones in the system, therefore the RAP replacement level becomes the dominating factor in determining the composite strength. This explanation also facilitates to explain the less reduction in the 7-day MOR compared to the 28-day MOR for the 20 percent replacement levels.



(a) 7 days



(b) 28 days

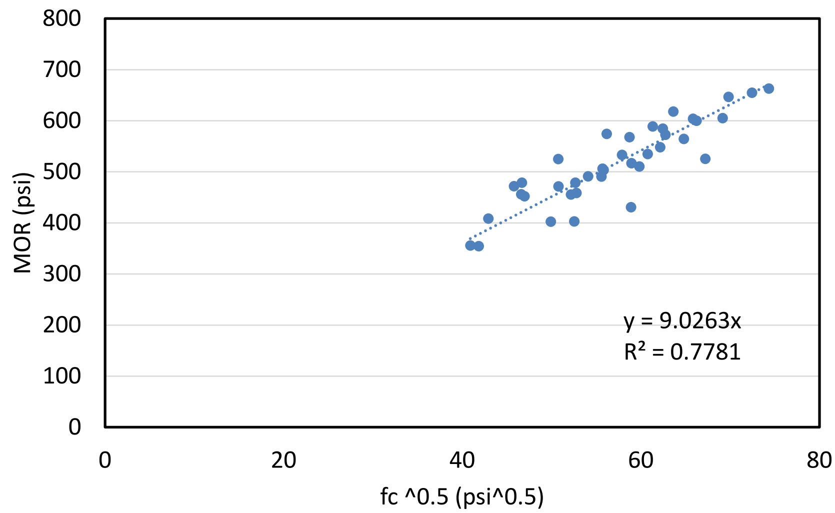


(c) 56 days

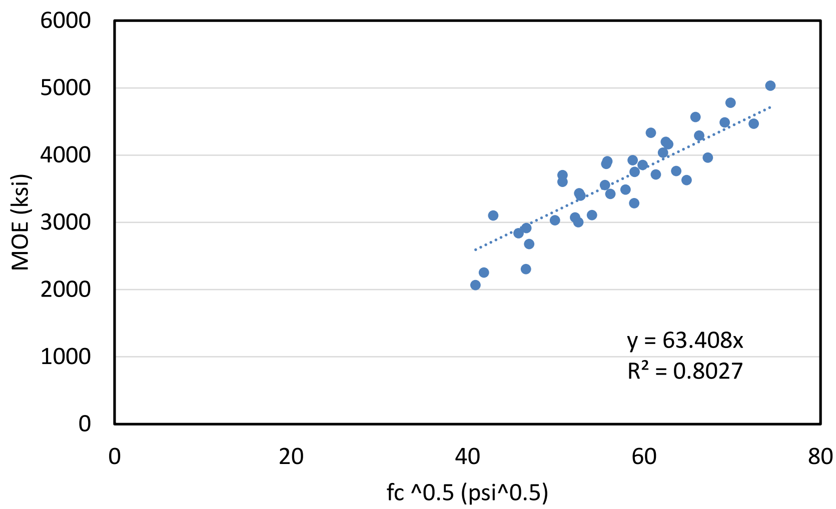
Figure 34. Comparison between Different Properties for 0.40_520 Mixes.

Modification of ACI Correlation Equations

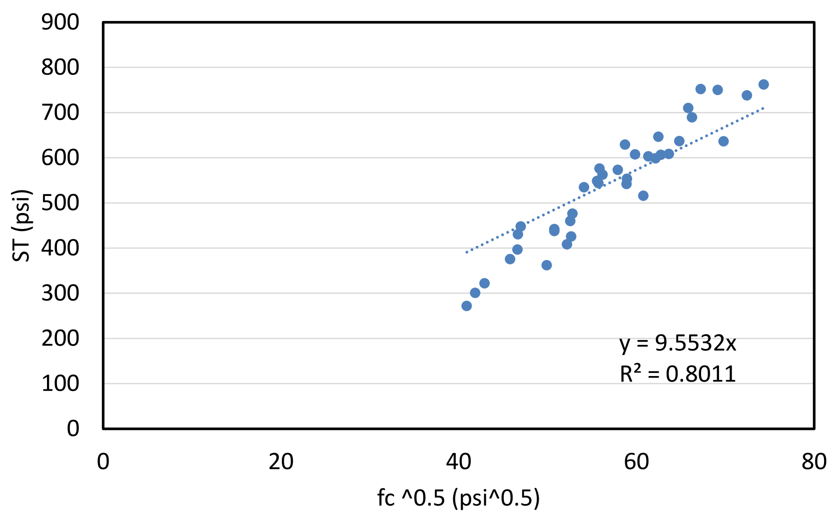
The ACI has adopted equations for predicting other mechanical properties from measured compressive strength. Those equations are only suitable for normal PC concrete. As discussed in the literature review, Tia et al. (2012) developed similar equations for the RAP concrete mixes. Based on the test results obtained in this project, an attempt has been made to develop similar set of equations for the concrete mixtures made of different types of RAP aggregates. To increase the number of data and make the equations as general as possible, all of the data from both the 0.45_656 mixes (Appendix D) and the 0.40_520 mixes were used. Figure 35 shows the correlations between compressive strength and MOE/MOR/STS. Table 19 shows the comparison of equations between ACI, Tia et al. (2012), and the current study.



(a) Correlation between MOR and fc



(b) Correlation between MOE and fc



(c) Correlation between STS and fc

Figure 35. Correlation between Mechanical Property and Compressive Strength.

Table 19. Comparison among the Equations Developed by Different Research.

ACI Equations for Conventional PCC	Tia et al. (2012) Equations for RAP Concrete	Current Project
$\mathbf{R = 7.5 \times f_c^{0.5}}$	$R = 9.25 \times f_c^{0.5}$	$R = 9.03 \times f_c^{0.5}$
$\mathbf{E_c = 57 \times f_c^{0.5}}$	$E_c = 54.665 \times f_c^{0.5}$	$E_c = 63.41 \times f_c^{0.5}$
$\mathbf{f_{ct} = 6.7 \times f_c^{0.5}}$	$f_{ct} = 1.5623 \times f_c^{0.6791}$	$f_{ct} = 9.55 \times f_c^{0.5}$

Table 19 shows that 1) By comparing the equations developed in this project with the ACI equations, researchers found the ACI equations underestimate the prediction of flexural strength, MOE, and STS of RAP concrete; and 2) Tia's equations versus ACI equations comparison indicates ACI equations overestimate the MOE and STS but underestimate the MOR. The inconsistency between the equations developed by two different studies for the RAP-PCC system is noticeable. Both coarse and fine RAP were used in making PCC mixes by the Tia et al.'s work and may have caused this inconsistency in the results. The PCC mixes made of both coarse and fine RAP may be softer in nature than PCC mixes made of coarse RAP alone.

The relationship between mechanical properties and asphalt fraction

Statistical models to describe the RAP-PCC mechanical properties with different RAP content were established through a regression analysis.

Since the different types of RAP have different asphalt binder content, instead of simply using the RAP replacement level, a global asphalt binder volumetric fraction (GABVF) is considered to be a more rigorous parameter to quantify the amount of the asphalt in the mix. The GABVF is computed in Equation 1:

$$\theta_g = \theta_l \times v \qquad \text{Equation 1}$$

Where
θ_g= GABVF (i.e., the volume of the asphalt binder by the total volume of the mix).
θ_l = the local asphalt binder volumetric fraction (i.e., the volume of the asphalt binder by the volume of the RAP).

V = the RAP volumetric fraction (i.e., the volume of the RAP by the total volume of the mix).

θ_l can be calculated in Equation 2:

$$\theta_l = \frac{w/G_b}{G_{RAP}} \qquad \text{Equation 2}$$

Where
w = the RAP asphalt binder content (weight fraction).
G_b = the specific gravity of asphalt binder.
G_{RAP} = the specific gravity of RAP.

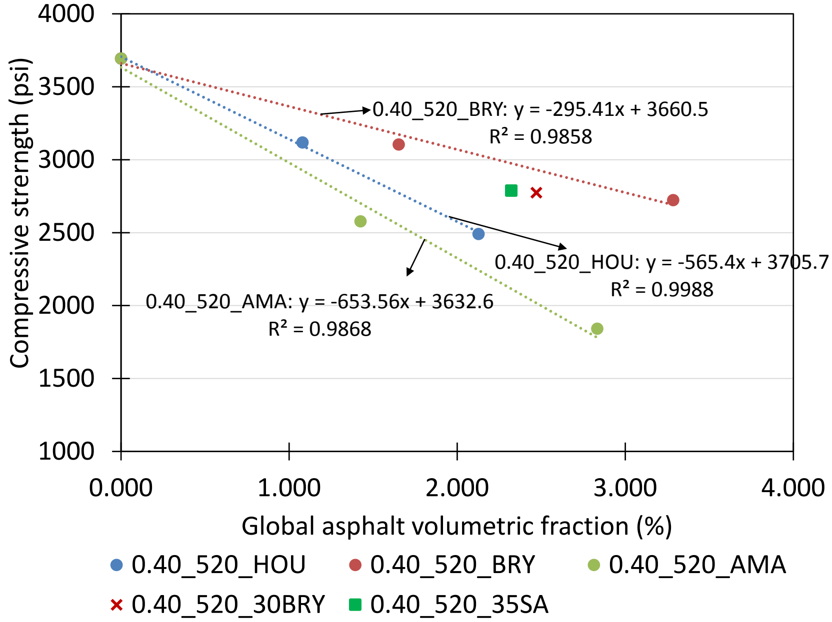
Table 20 lists the mechanical properties and the GABVF for the 0.40_520 mixes. Since the requirements for the compressive strength and the flexural strength are in the TxDOT specification, only these two parameters are included in the analysis.

Table 20. A Summary of Mechanical Properties for Different Mixes.

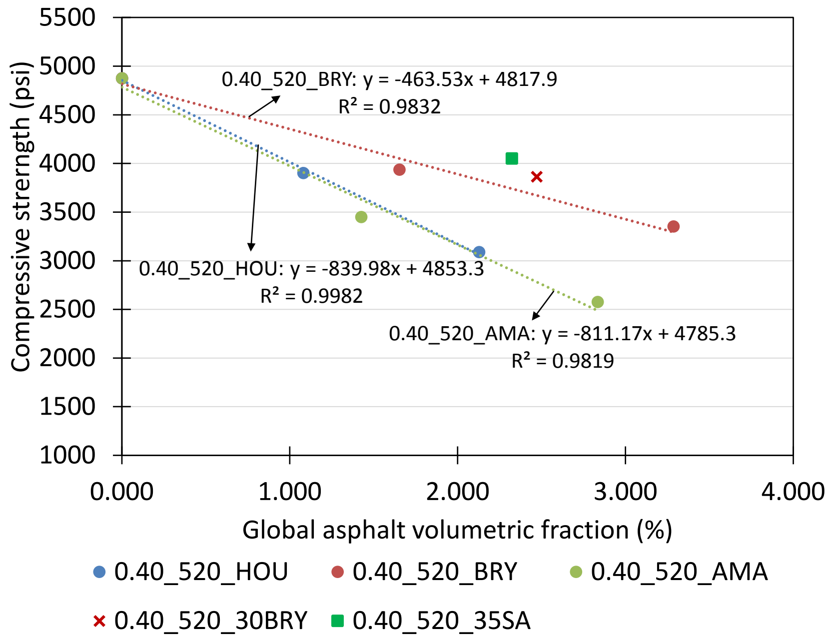
Mix ID	GABVF (%)	7-day fc (psi)	28-day fc (psi)	7-day MOR (psi)	28-day MOR (psi)
0.40_520_REF	0.000	3694	4875	535	647
0.40_520_20HOU	1.080	3119	3902	504	585
0.40_520_40HOU	2.127	2491	3089	402	491
0.40_520_20BRY	1.653	3105	3937	506	573
0.40_520_40BRY	3.285	2724	3353	456	533
0.40_520_20AMA	1.425	2578	3449	471	568
0.40_520_40AMA	2.834	1843	2577	408	525

Statistical regression analysis was then performed to establish correlations between the mechanical properties and the GABVF. Figure 36 and Figure 37 show the results. As can be seen in the figures, the compressive strength and flexural strength have strong linear relationship with the GABVF. A generalized model was then proposed in Figure 38. In this model, the slope k is defined as the rate of deterioration. It represents how fast the addition of the RAP material negatively affects the strength reduction of the studied mixtures. Obviously, a lower k is desired because a lower k can allow more RAP in the system before the strength properties become unacceptable. Researchers believe that k is largely related to the RAP properties and the mix design. The coefficient b is the interception of the line with the y axis, and it should be close to the reference mix property. Table 21 tabulates the coefficients for the different mixes tested in this project. From Table 21, the 0.40_520_BRY mix had the lowest rate of deterioration for both compressive strength and flexural strength at both 7- and 28-day curing ages. Compared to 0.40_520_HOU and 0.40_520_AMA, the k values for the 0.40_520_BRY were only approximately 50 percent of the k values for the other two mixes. This finding demonstrates that the optimized gradation (characteristics of 0.40_520_BRY mixture) increases mix strength, allowing more RAP in the mix.

Additional two mixes were cast and tested afterward for the further verification of the prediction model and the dense gradation benefit. The mixes were 0.40_520_30BRY and 0.40_520_35SA, and their results are plotted in Figure 36 and Figure 37. As can be shown, the 0.40_520_30BRY results matched well in the 0.40_520_BRY regression curve for both 7-day and 28-day cases (especially for the flexural strength case), indicating that the use of the regression equations to predict mix properties is valid. The 7-day results for the 0.40_520_35SA show that although this RAP concrete mix has slightly higher rates of deterioration than those for the BRY RAP concrete, it is clearly better than both of the gap graded RAP concrete cases (0.40_520_HOU and 0.40_520_AMA). For the 28-day results, the 0.40_520_35SA shows the results among all the mixes. Considering that SA_C2 is very well-graded with almost no agglomeration problem, plus the 0.40_520_35SA mix yields a position very close to the middle point of the workability box in the CF chart in Figure 16, researchers concluded that 0.40_520_35SA is another good example to manifest the dense gradation benefit.

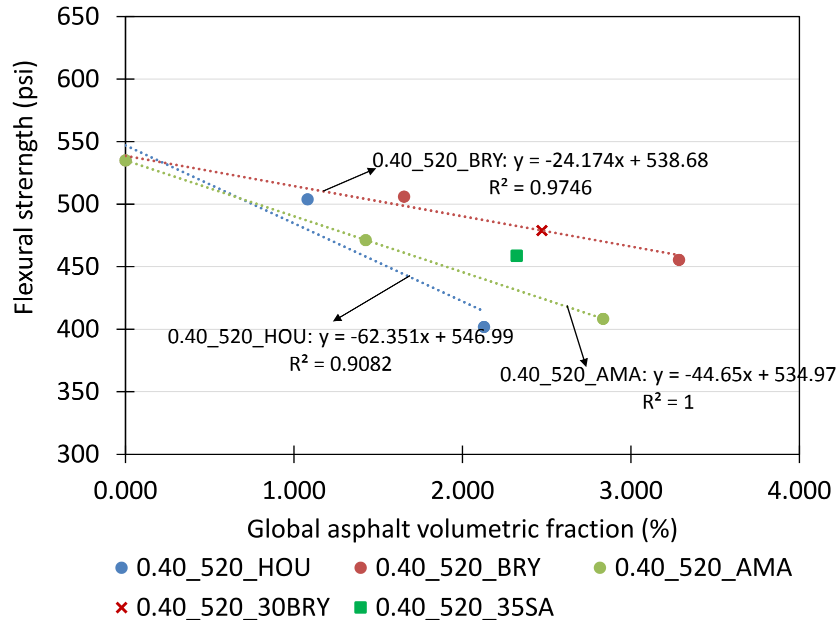


(a) 7 days

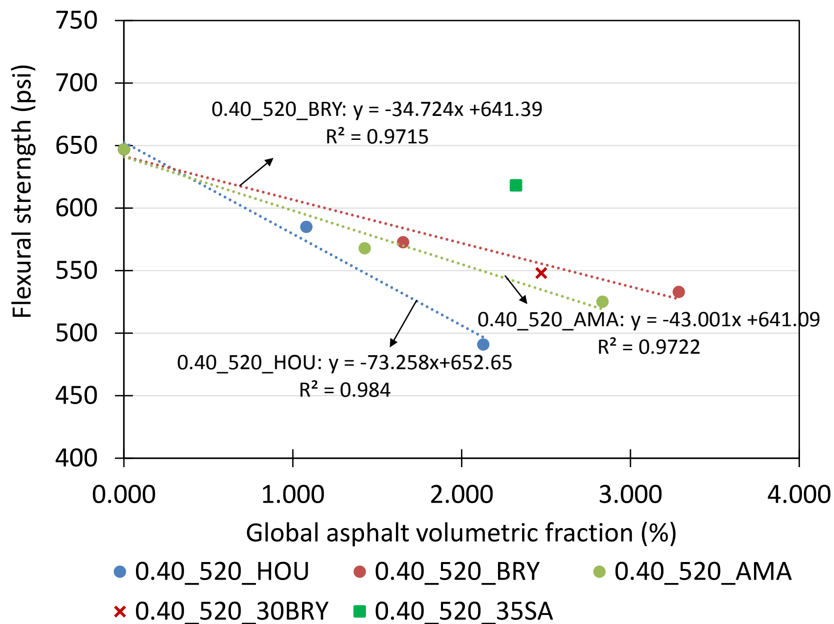


(b) 28 days

Figure 36. Correlations between Asphalt Fraction and Compressive Strength.



(a) 7 days



(b) 28 days

Figure 37. Correlations between Asphalt Fraction and Flexural Strength.

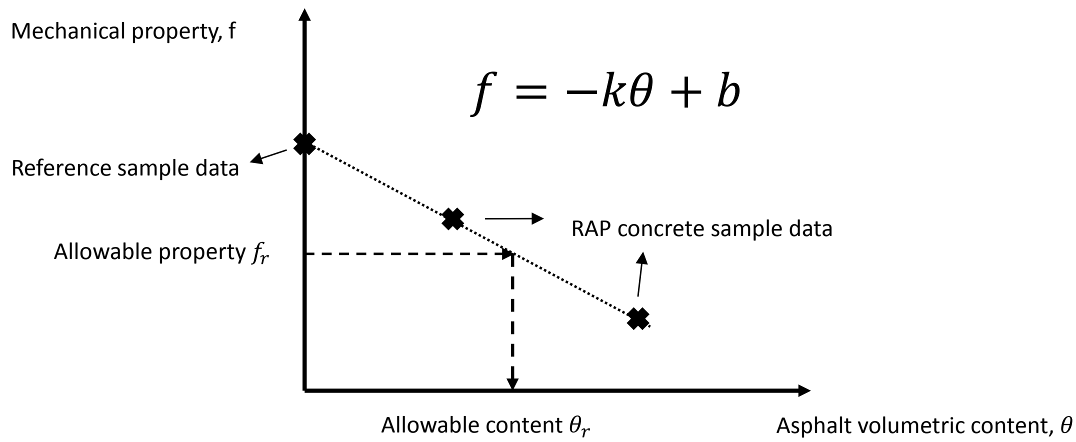


Figure 38. Correlations between the Mechanical Property: Model.

Table 21. Regression Coefficients for Different Mixes.

Mix ID	7 day fc		28 day fc		7 day MOR		28 day MOR	
	k (psi)	b (psi)	k (psi)	b (psi)	k (psi)	b (psi)	k (psi)	b (psi)
0.40_520_HOU	565.40	3705.7	839.98	4853.3	62.351	546.99	73.258	652.65
0.40_520_BRY	295.41	3660.5	463.53	4817.9	24.174	538.68	34.724	641.39
0.40_520_AMA	653.56	3632.6	811.17	4785.3	44.650	534.97	43.001	641.09

Optimum RAP Replacement for Class P Concrete

Once the regression relationships are established, the allowable GABVF can be easily found when the allowable value for the property is given, and the corresponding RAP replacement level can be back-calculated according to the mix design. The requirements for class P concrete in Texas are well specified in the specification, as shown in Table 22. Using the regression equations in Figure 37, the allowable RAP replacement level for different RAP types was obtained and summarized in Table 23.

Table 22. TxDOT Specification for Class P Concrete.

	7 days	28 days
Compressive strength (psi)	3200	4000
Flexural strength (psi)	450	570

Table 23. Allowable RAP Replacement Level for Different Mixes Based on Different Criteria.

Mix ID	7-day fc	28-day fc	7-day MOR	28-day MOR
0.40_520_HOU	16%	19%	29%	20%
0.40_520_BRY	18%	21%	44%	24%
0.40_520_AMA	9%	13%	27%	23%

Table 23 indicates that the allowable AMA RAP replacement level is much less compared to the HOU RAP concrete and BRY RAP concrete if the compressive strength criteria are used. The slope of the linear regression line for the BRY RAP concrete is the lowest. As a result, the allowable replacement level turns out to be the highest for 0.40_520_BRY. Considering the compressive strength, the allowable replacement level for the 28-day criteria is higher than that for the 7-day criteria, while the flexural strength case is opposite. This can be explained as: for the compressive strength in the TxDOT specification, the rate of increase from 7-day requirement (3200 psi) to 28-day requirement (4000 psi) is 25 percent. Figure 26(c) shows that the rate of increase of the RAP concrete mixes over the same time interval were higher or at least close to 25 percent. With a higher strength increase rate, the allowable replacement level at 28 days is expected to be higher than that at 7 days. However, for the flexural strength case, the rate of increase in the specification is 26.6 percent (from 450 psi to 570 psi), while most of the RAP concrete mixes showed smaller rate of increase (Figure 30(c)), which possibly leads to a lower (lower than 7 days replacement level) allowable replacement in 28 days.

Since there is an inconsistency of the allowable RAP replacement level satisfying the requirements of strength (both compressive and flexural) at both 7 and 28 days, assigning a common replacement level is questionable. The flexural strength is considered to be an important and relevant parameter related to concrete pavement performance because concrete is weak in tension and its tensile strength should be strictly controlled. Therefore, assigning replacement level based on flexural strength criteria may be more relevant and practical. Additionally, RAP concrete had much slower flexural growth over time compared to that corresponding to the specification requirements. Meeting the 28-day flexural strength requirement is considered more conservative. Given that the 28-day flexural strength is 570 psi, using the modified ACI correlation equation in Equation 3 for the RAP concrete tested in this problem, the corresponding 28-day compressive strength requirement can be set as 3993 psi.

$$R = 9.02 \times f_c^{0.5} \qquad \text{Equation 3}$$

Based on 7 days MOR criteria, a higher level of RAP replacement is possible (i.e., 44 percent for concrete mixes made of BRY RAP and 27–29 percent for concrete mixes made of AMA and HOU RAPs, respectively). A further research study is highly warranted in order to verify whether a PCC pavement slab made of PCC mix with higher level of RAP replacement (based on 7 days MOR criteria) can still perform better and satisfying 28 days MOR criteria may not be required.

Durability

The durability of the studied PCC concrete mixes made of different types of RAP with varying replacement level was evaluated by performing some relevant durability testing such as freeze-thaw resistance testing, permeability testing, restrained shrinkage testing, and abrasion resistance testing.

Freeze-Thaw Resistance

Air void characterization using PCC containing RAP was performed according to ASTM C457 test method. The air void parameters were determined for concrete 0.4_520_BRY, 0.4_520_HOU, and reference mixes. Table 24 presents the results. The results show that replacing virgin coarse aggregate (≤40 percent) by RAP aggregate does not necessarily bring any significant changes to the air distribution parameters. This indirectly suggests that PCC concrete made by RAP will have adequate freeze-thaw resistance especially less demand situation in Texas.

Table 24. Air Void Characterization in Hardened Concrete Samples.

	0.40_520_ REF	0.40_520_ 20HOU	0.40_520_ 40HOU	0.40_520_ 20BRY	0.40_520_ 40BRY
Air Content (A), %	2.6%	6.3%	6.3%	4.0%	4.8%
Void Frequency (n)	0.01	0.04	0.04	0.02	0.03
Paste Content (p), %	34.8%	30.0%	22.2%	46.0%	34.1%
Paste-Air ratio (p/A), %	13.6	4.8	3.5	11.6	7.1
Average chord length (l), mm	1.79	1.71	1.64	1.76	1.70
Specific Surface (α), mm^-1	2.2	2.3	2.4	2.3	2.4
Spacing Factor (L), mm	0.69	0.53	0.75	0.45	0.37

The direct freeze-thaw testing by following ASTM C666 was conducted to compare with the air avoid parameters presented in Table 24. Figure 39 shows the result and indicates that the RAP-PCC samples even had a higher durability factor than the plain PCC sample.

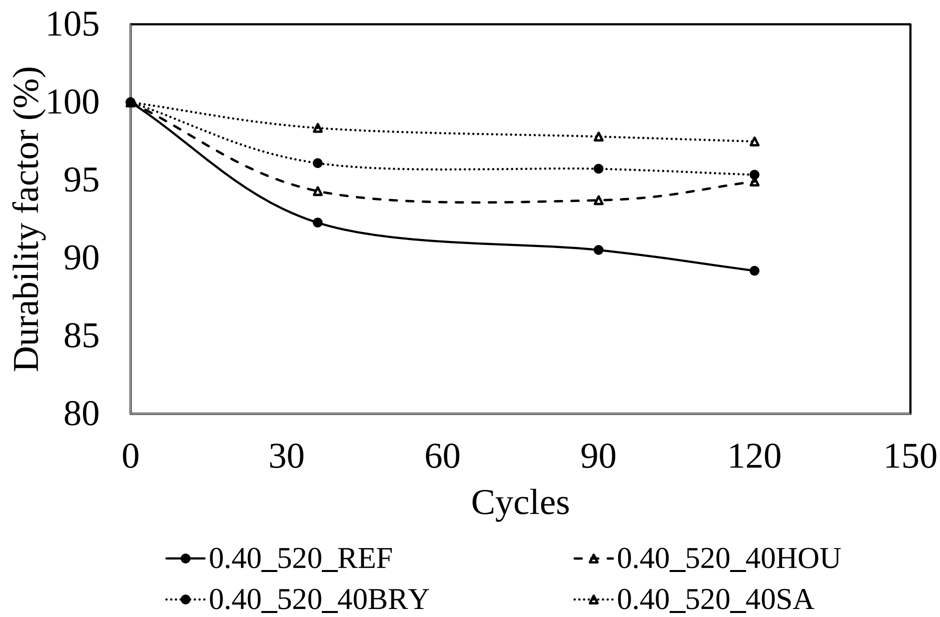


Figure 39. Freeze-Thaw Test Results.

Permeability

To measure permeability of RAP concrete mixes, electrical resistivity measurement was conducted. The electrical resistivity measurements were made using the Giatec RCON2 concrete bulk resistivity meter. Figure 40 shows a picture of the electrical resistivity test.

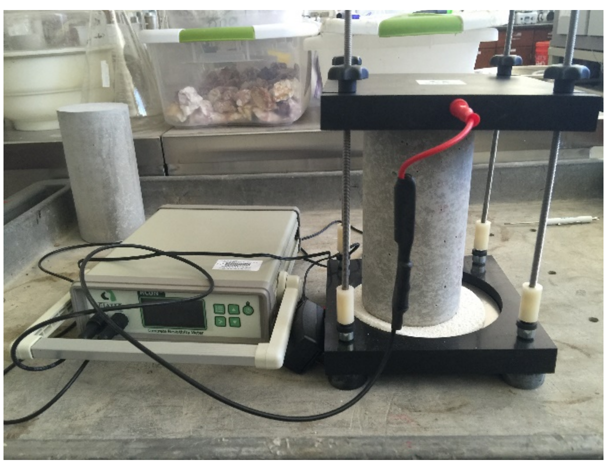


Figure 40. Electrical Resistivity Test.

Figure 41 shows the results for the electrical resistivity of concrete mixes containing different types of RAP with varying replacement levels at 56 days curing age. A perusal of Figure 41 indicates that the resistivity values for all the studied concrete mixes are similar and comparable. Several researches (Ramezanianpour et al. 2011; Riding et al. 2008; Wee et al. 2000) indicated that there is very strong correlation between the electrical resistivity and rapid chloride permeability (RCP). Table 25 shows the relationship chart between the bulk electrical resistivity and the RCP. The results indicate that all the studied RAP concrete mixes and the reference sample show low levels of electrical resistivity/chloride penetration. Therefore, replacing certain portion of virgin coarse aggregate by coarse RAP (i.e., ≤ 40 percent) does not introduce any change in permeability property of the concrete.

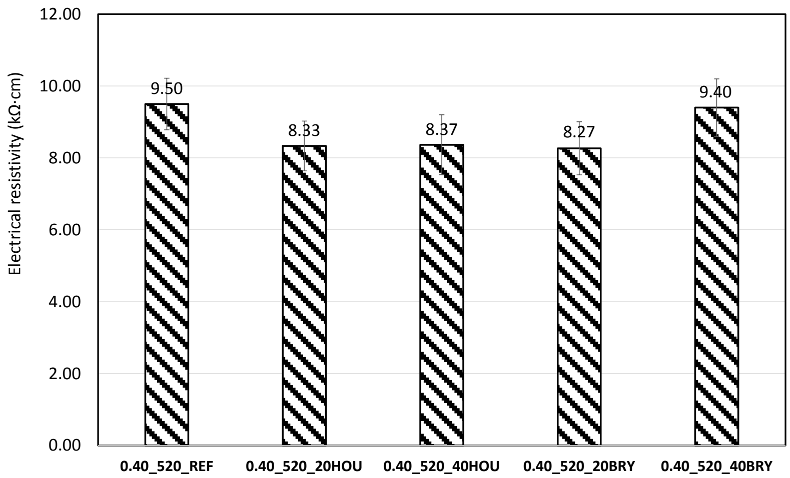


Figure 41. Electrical Resistivity of RAP Concrete.

Table 25. Relationship between Electrical Resistivity and the Rapid Chloride Permeability.

Chloride Penetration Level	56-Day Rapid Chloride Permeability Charge Passed (Coulombs)	28-Day Bulk Electrical Resistivity of Saturated Concrete (kΩ.cm)
High	>4000	<4
Moderate	2000–4000	4–8
Low	1000–2000	8–16
Very Low	100–1000	16–190
Negligible	<100	>190

Restrained Shrinkage

The ring test, followed by ASTM C1581, was used to evaluate the restrained shrinkage property of some selective RAP concrete in this project (Figure 42).

Figure 42. Ring Test: Concrete Ring at Age of 1 Days (Left) and at Age of 28 Days.

Figure 43 presents the reasonably good data that were obtained. The figure shows that the 0.40_520_40HOU mix had slightly higher amount of tensile strain than the reference mix, while the 0.40_520_40BRY mix had lower amount of tensile strain, which may be a benefit from dense gradation mix design. The formation of any crack till 28 days of testing period was not observed visually in any of the ring specimens. This possibly suggests that replacing certain portion of virgin coarse aggregate by coarse RAP (i.e., ≤ 40 percent) does not cause any considerable increase of shrinkage strain of the RAP concrete.

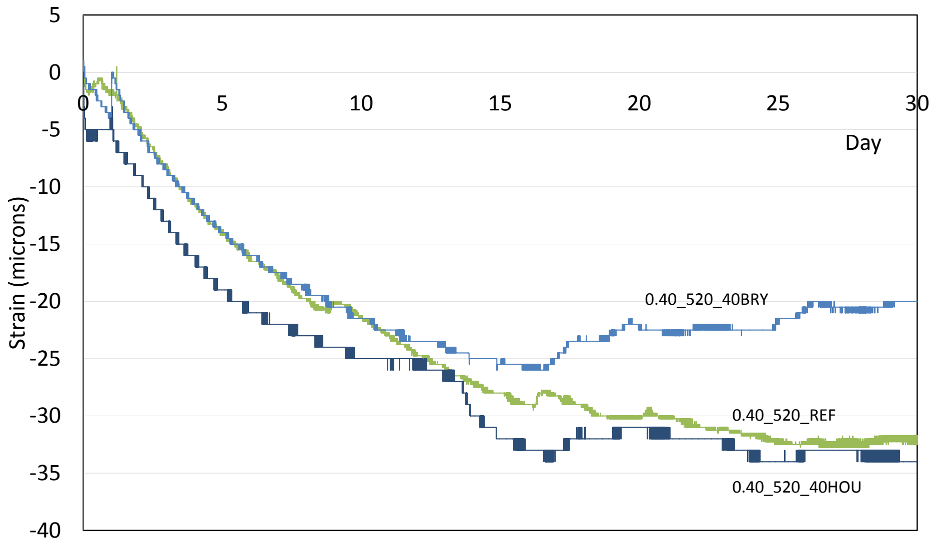


Figure 43. Ring Test Results.

Abrasion Resistance

The abrasion resistance test was performed according to ASTM C779 procedure A using the revolving disks (Figure 44). Figure 45 summarizes the wear depths after 30 min and 60 min testing. No significant difference between the RAP-PCC samples and the reference sample was reported in Figure 45.

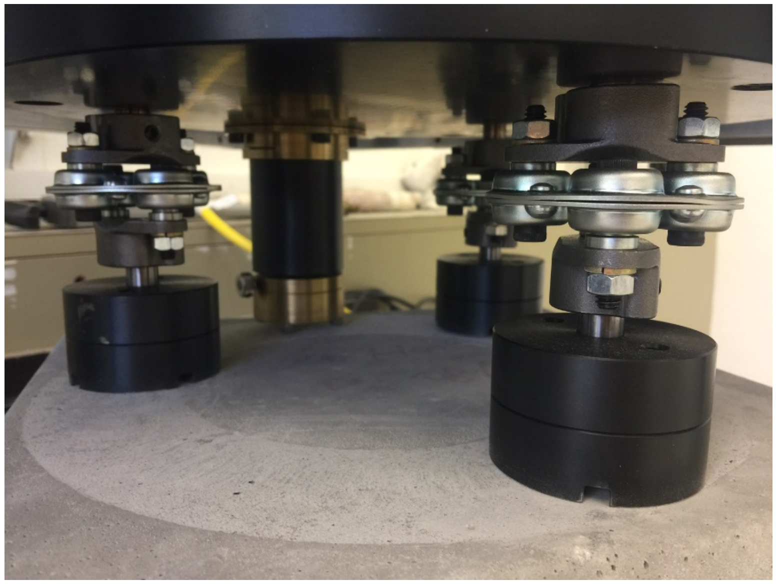


Figure 44. Abrasion Resistance Test.

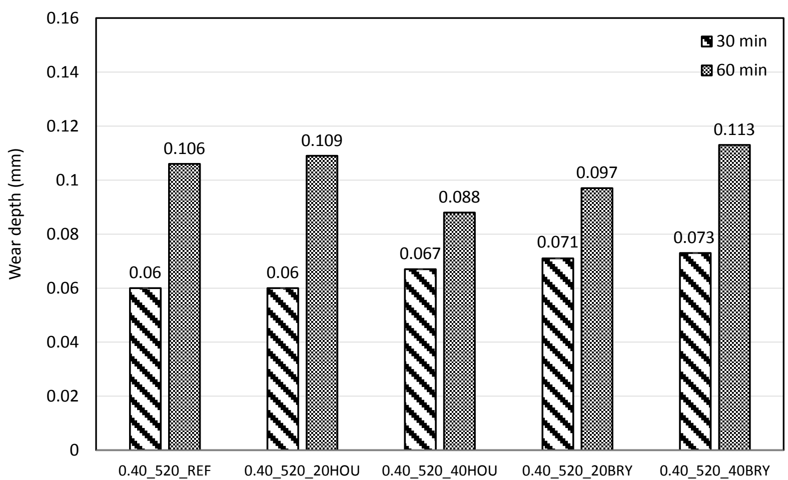


Figure 45. Abrasion Test Results.

USE OF RAP AGGREGATES TO MAKE LOW STRENGTH CONCRETE

The findings in the literature review (refer to Chapter 1) suggested that the inclusion of fine RAP in PCC mixture invariably causes severe reduction in mechanical properties. Since the strength requirement for Class P is relatively high, researchers decided not to use any fine portion of RAP to produce RAP-PCC for pavement applications in this chapter. However, for other concrete classes whose strength requirements are not as high as paving concrete, a combined use of both coarse and fine RAP can probably be allowed. The use of fine RAP not only maximizes the RAP usage, but also saves efforts and expense to fractionate RAP.

According to the TxDOT standard specifications for construction and maintenance of highways, streets, and bridges, concrete mix designs can be categorized into different classes (TxDOT

2014). Table 26 summarizes the requirements for different concrete classes that specified in Item 421. A peruse of mix design information in Table 13 indicates the tested 0.40_520_series are well qualified as Class A, Class B, Class C, Class E, Class F, Class H, Class S, and Class SS, as long as the design strength requirement is met (Column 2 of Table 26). To meet those design strength requirements, the maximum RAP replacement level can be determined based on the methodology that is discussed below. Because there is no specified value for compressive strength requirement, the RAP-PCC applications for Class K, Class HES, Class “X”(HPC), and Class “X”(SRC) is not discussed.

Table 26. Different Concrete Class Specified in Item 421.

Class of Concrete	Design Strength,[1] Min f′c (psi)	Max w/cm Ratio	Coarse Aggregate Grades [2,3,4]	Cement Types	Mix Design Options	Exceptions to Mix Design Options	General Usage[5]
A	3,000	0.60	1–4, 8	I, II, I/II, IL, IP, IS, IT, V	1, 2, 4, and 7	When the cementitious material content does not exceed 520 lb/cy, Class C fly ash may be used instead of Class F fly ash.	Curb, gutter, curb and gutter, conc. retards, sidewalks, driveways, back-up walls, anchors, non-reinforced drilled shafts
B	2,000	0.60	2–7				Riprap, traffic signal controller foundations, small roadside signs, and anchors
C6	3,600	0.45	1–6	I, II, I/II, IP, IS, IT,7 V	1–8		Drilled shafts, bridge substructure, bridge railing, culverts except top slab of direct traffic culverts, headwalls, wing walls, inlets, manholes, concrete traffic barrier (cast-in-place)
E	3,000	0.50	2–5	I, II, I/II, IL, IP, IS, IT,7 V	1–8	When the cementitious material content does not exceed 520 lb/cy, Class C fly ash may be used instead of Class F fly ash.	Seal concrete
F	Note 8	0.45	2–5	I, II, I/II, IP, IS, IT,7V			Railroad structures; occasionally for bridge piers, columns, or bents
H6	Note 8	0.45	3–6	I, II, I/II, III, IP, IS, IT,7 V	1–5	Do not use Type III cement in mass placement concrete. Up to 20% of blended cement may be replaced with listed SCMs when Option 4 is used for precast concrete.	Precast concrete, post-tension members
S6	4,000	0.45	2–5	I, II, I/II, IP, IS, IT,7V	1–8		Bridge slabs, top slabs of direct traffic culverts, approach slabs
P	See Item 360, “Concrete Pavement.”	0.50	2–3	I, II, I/II, IL, IP, IS, IT, V	1–8	When the cementitious material content does not exceed 520 lb/cy, Class C fly ash may be used instead of Class F fly ash.	Concrete pavement
CO6	4,600	0.40	6	I, II, I/II, IP, IS,	1–8		Bridge deck concrete overlay

Class of Concrete	Design Strength,[1] Min f'c (psi)	Max w/cm Ratio	Coarse Aggregate Grades [2,3,4]	Cement Types	Mix Design Options	Exceptions to Mix Design Options	General Usage[5]
LMC6	4,000	0.40	6–8	IT,7 V			Latex-modified concrete overlay
SS6	3,600	0.45	4–6			Use a minimum cementitious material content of 658 lb/cy of concrete	Slurry displacement shafts, underwater drilled shafts
K6	Note 8	0.40	Note 8	I, II, I/II, III IP, IS, IT,7 V			Note 8
HES	Note 8	0.45	Note 8	I, IL, II, I/II, III		Mix design options do not apply. 700 lb of cementitious material per cubic yard limit does not apply.	Concrete pavement, concrete pavement repair
"X" (HPC) 6,9,10	Note 11	0.45	Note 11	I, II, I/II, III IP, IS, IT,7 V	1–5, and 8	Maximum fly ash replacement for Options 1 and 3 may be increased to 45%. Up to 20% of a blended cement may be replaced with listed SCMs for Option 4. Do not use Option 8 for precast concrete.	
"X" (SRC) 6,9,10	Note 11	0.45	Note 11	I/II, II, IP, IS, IT,7 V	1–4 , and 7	Do not use Class C Fly Ash Type III-MS may be used where allowed. Type I and Type III cements may be used with Options 1–3, with a maximum w/cm of 0.40. Up to 20% of blended cement may be replaced with listed SCMs when Option 4 is used for precast concrete. Do not use Option 7 for precast concrete.	

1. Design strength must be attained within 56 days.
2. Do not use Grade 1 coarse aggregate except in massive foundations with 4 in. minimum clear spacing between reinforcing steel bars, unless otherwise permitted. Do not use Grade 1 aggregate in drilled shafts.
3. Use Grade 8 aggregate in extruded curbs unless otherwise approved.
4. Other grades of coarse aggregate maybe used in non-structural concrete classes when allowed by the Engineer.
5. For information only.
6. Structural concrete classes.
7. Do not use Type IT cements containing > 5% limestone.
8. As shown on the plans or specified.
9. "X" denotes class of concrete shown on the plans or specified.
10. (HPC): High Performance Concrete, (SRC): Sulfate Resistant Concrete.
11. Same as class of concrete shown on the plans.

The correlations between the mechanical properties and the GABVF for class P concrete have been generated in the previous section. However, those correlations were made using the data for concrete samples containing coarse RAP up to 40 percent (the GABVF ranging from 0 to 3.285 percent) only, so they were only valid within this asphalt fraction range. In order to predict the allowable RAP replacement level for different classes identified above, relationships between the mechanical property (i.e., compressive strength) and the GABVF covering a much wider range are needed.

A series of PCC samples containing both coarse and fine RAP were designed, produced, and tested. The coarse RAP used was from Bryan District (ie., BRY_C), while the fine portion of BRY RAP (passing No. 8 sieve), BRY_F, was served as fine RAP in the mixture. Both coarse and fine virgin aggregates were replaced by the BRY_C and the BRY_F on volume basis, respectively. The replacement levels were selected as 20 percent, 40 percent, 70 percent, and 100 percent. For example, 20% replacement level means both coarse and fine virgin aggregates were replaced by 20% coarse and fine RAP materials, respectively. All the other mix design parameters remained same with what was used in the previous Class P mixtures. The mix ID was assigned in the following format with a similar manner:

w/cm_cementitious content_coarse RAP replacement level+RAP type / fine RAP replacement level+RAP type

Example: 0.40_520_20BRY/20BRY represents a mix that has 0.40 w/cm ratio, 520 lb/cy cementitious content, and BRY_C to replace 20 percent of virgin coarse aggregate and BRY_F to replace 20 percent of virgin sand.

Table 27 summarizes the mix design.

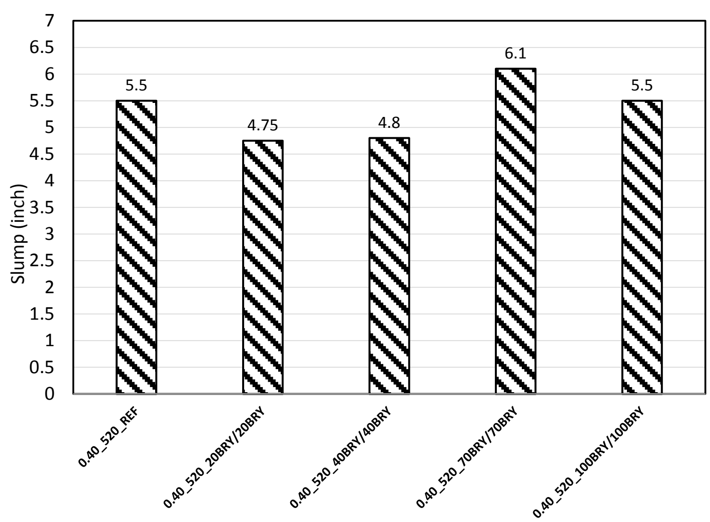
Table 27. Mix Design for the PCC Mixes Containing Both Coarse and Fine RAP.

	0.40_520_REF	0.40_520_20BRY/20BRY	0.40_520_40BRY/40BRY	0.40_520_70BRY/70BRY	0.40_520_100BRY/100BRY
Cement (lb/cy)	525	525	525	525	525
Fly Ash (lb/cy)	131	131	131	131	131
Virgin coarse aggregate (lb/cy)	1783	1373	1002	481	0
Coarse RAP (lb/cy)	0	323	629	1055	1444
Virgin Fine aggregate (lb/cy)	1296	1049	780	383	0
Fine RAP (lb/cy)	0	262	520	894	1245
Water Reducer (fl oz/cy)	13.1	13.1	13.1	13.1	13.1
Air Entraining Agent (fl oz/cy)	1.968	1.968	1.968	1.968	1.968
Water (lb/cy)	295	295	295	295	295

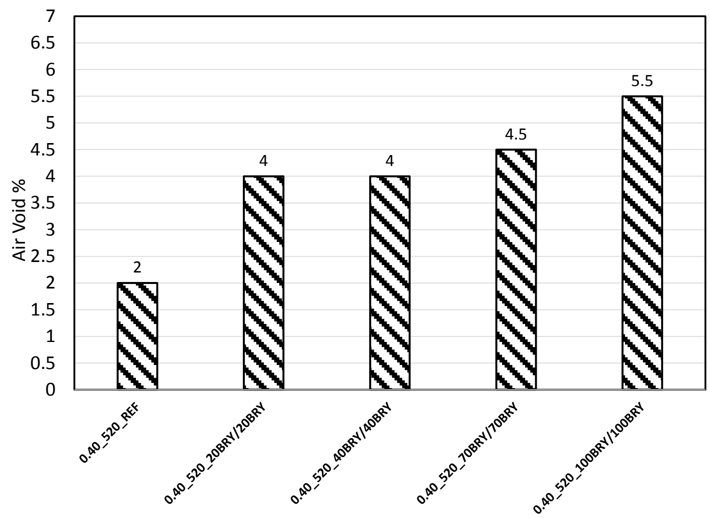
Fresh Concrete Properties Test Results

Figure 46 indicates that the combined use of the coarse and fine RAP had little effect on slump and air content measurements. However, the mixtures with 70 percent and 100 percent replacement levels appeared to be dry. During the slump test, a phenomenon similar to structural collapse (i.e., mixture with poor shear resistance) (Figure 47) was observed for the mixture with 100 percent replacement level, which was very different from the reference sample. This finding suggests that the conventional slump test might not be a good indication of RAP-PCC workability. As can be shown in this example, RAP-PCC samples with high RAP replacement appeared to have good slump values but their workability were very different from that of the conventional concrete. The RAP absorbed water during the mixing to form a dry mixture, but it also released the water very easily when the mix was vibrated or tamped.

It was suspected that the above mentioned behavior during slump test of the mixture with 100 percent replacement level was possibly due to insufficient w/cm. An additional set of mixes with a higher w/cm (0.45) was produced. Table 28 shows the slump tests results of the new mixes. Although the 0.45_520_100BRY/100BRY appeared to be a more flowable and uniform mixture (Figure 48), it still suffered a structural collapse (Figure 49), just like the 0.40_520_100BRY/100BRY. So, it was concluded that a structural collapse is a typical slump test observation for the RAP-PCC with very high replacement level, and this indicates that the conventional slump test may not be able to properly characterize the workability property of such mixes. It is to be noted that the slump of 0.45_520_100BRY/100BRY mix is lower than that of 0.40_520_100BRY/100BRY mix. This possibly indicates inconsistency and variability on measuring slump for PCC containing higher amounts of RAP.



(a) Slump measurement



(b) Air content measurement

Figure 46. Fresh Properties of 0.40_520_BRY/BRY Mixes.

Figure 47. A Structural Collapse of the 0.40_520_100BRY/100BRY.

Figure 48 A Good Finished Surface of the 0.45_520_100BRY/100BRY.

Figure 49. A Structural Collapse of the 0.45_520_100BRY/100BRY.

Table 28. Slump Tests of the 0.45_520_BRY/BRY Mixes.

Mix ID	Slump
0.45_520_40BRY/40BRY	7.5
0.45_520_70BRY/70BRY	7.0
0.45_520_100BRY/100BRY	3.75

Hardened Concrete Properties Test Results

Table 29 shows the compressive strength for the PCC containing both coarse and fine RAP. Table 29 indicates that adding both coarse and fine RAP into PCC led to a significant reduction in compressive strength. This suggests that that the use of fine RAP to make class P concrete is not recommended. The results also show that with increase of w/cm from 0.40 to 0.45, the improvement of compressive strength was clearly visible for the mixtures with replacement levels ≥ 40 percent. However, more strength data on the RAP-PCC containing higher amounts of fine RAP and with varying w/cm need to be generated in the future in order to validate this finding as well as determine an optimum w/cm.

Table 29. Test Results for the PCC Mixes containing Both Coarse and Fine RAP.

Mix ID	Curing Time	Compressive Strength	
		Mean (psi)	Coefficient of variance (COV) (%)
0.40_520_REF	7-day	3694	1.78
	28-day	4875	3.87
	56-day	5525	2.22
0.40_520_20BRY/20BRY	7-day	2248	7.05
	28-day	2936	1.53
	56-day	3653	2.42
0.40_520_40BRY/40BRY	7-day	1241	2.21
	28-day	1597	3.11
	56-day	2164	7.41
0.40_520_70BRY/70BRY	7-day	914	5.16
	28-day	1243	0.95
	56-day	1553	3.97
0.40_520_100BRY/100BRY	7-day	845	5.42
	28-day	1075	1.48
	56-day	1231	2.34
0.45_520_40BRY/40BRY	7-day	1758	1.11
	28-day	2369	0.86
	56-day	2809	3.98
0.45_520_70BRY/70BRY	7-day	1331	0.73
	28-day	1820	11.76
	56-day	2032	0.10
0.45_520_100BRY/100BRY	7-day	941	3.96
	28-day	1625	5.89
	56-day	1473	6.69

Optimum RAP Replacement for Different Class Concrete

In order to perform a robust regression analysis between the compressive strength and a wide range of GABVF, all of the measured experimental data in this project (i.e., 0.45_656 series, 0.40_520_series and 0.40_520_BRY/BRY series) were used. Tia et al. (2012)'s research used both coarse and fine RAP to replace aggregates in PCC mixtures, which yielded a very high range of GABVF, so their results were also included in the database for the regression analysis. Table 30 presents a summary of all the data used for the regression analysis.

Table 30. A Summary of the RAP-PCC Compressive Strength Data.

Data Source	w/cm	Cementitious Content (lb/cy)	RAP Type	RAP Source	Replacement Level	Curing Date
This study	0.40	520	Coarse RAP	HOU, BRY, AMA, SA	Coarse virgin aggregate replaced by 20%, 30%, 35%, 40% coarse RAP	7d, 28d, 56d
	0.40	520	Coarse + fine RAP	BRY	Both coarse and fine virgin aggregates replaced by 20%, 40%, 70%, 100% coarse and fine RAP	7d, 28d, 56d
	0.45	656	Coarse RAP	HOU	Coarse virgin aggregate replaced by 20%, 40%, 70%, 100% coarse RAP	7d, 28d, 56d
FDOT (Tia et al. 2012)	0.50	500	Coarse +fine RAP	RAP-1, RAP-2, RAP-3, RAP-4	Both coarse and fine virgin aggregates replaced by 20%, 40%, 70%, 100% coarse and fine RAP	7d, 28d

The statistics software, JMP, developed by SAS Institute, was used to perform the regression analysis. The Microsoft Excel was also used for some simple statistical applications. From Table 30, the w/cm (wc), cementitious content (cc), and the GABVF (θ) were recognized as independent variables, and the percent reduction (%red) in compressive strength was set as dependent variable. The GABVF (θ) can be determined using Equation 1 and 2. The percent reduction in compressive strength is defined in Equation 4:

$$\%\,reduction = \frac{f_c'(reference\ PCC) - f_c'(RAP\ PCC)}{f_c'(reference\ PCC)} \times 100\% \qquad \text{Equation 4}$$

To identify the significance of each independent variable on the dependent variable, a linear multiple regression analysis was first performed using the compressive strength data at 7 days, 28 days, and 56 days, respectively. In order to maintain the model simplicity, the interaction effects between the independent variables were not evaluated. Table 31 shows the analysis results. From Table 31, the independent variables wc and cc had p-values that were higher than 0.05, which means that researchers could not reject the null hypothesis that these variables have no effect on the model. The p-value of the independent variable θ was lower than 0.0001 for all three cases (i.e., shows 95 percent confidence to reject the null hypothesis that θ has no effect on the model). Therefore, wc and cc are insignificant variables, while θ is a significant variable. No 56-day compressive strengths data were available in Tia et al. (2012)'s research, and the lower degree of freedom of these two variables enabled the p-value calculations.

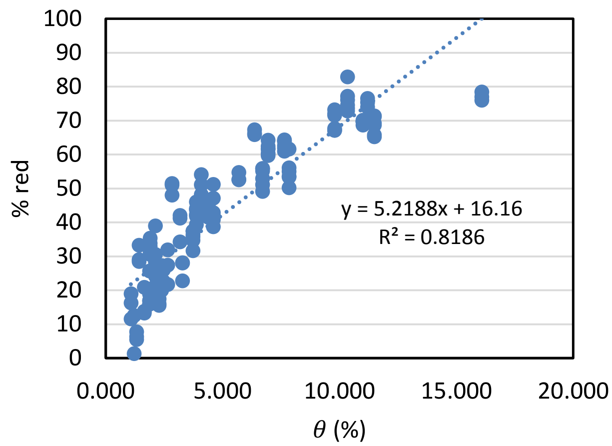
Table 31. Significance of Each Independent Variable.

Curing Date	P-value		
	w/cm (wc)	Cementitious content (cc)	Global asphalt volumetric content (θ)
7-day	0.21973	0.71525	<0.0001
28-day	0.0749	0.9384	<0.0001
56-day	-	-	<0.0001

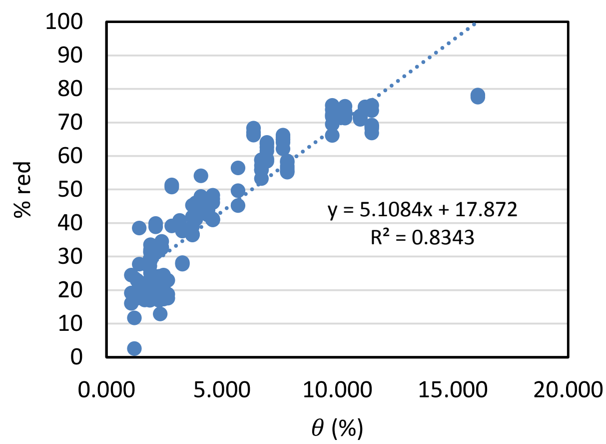
Given the fact that wc and cc are insignificant variables, a linear regression was performed by only using the significant variable θ. The regression equation can be assigned as:

$$\%red = k\theta + b \quad \text{Equation 5}$$

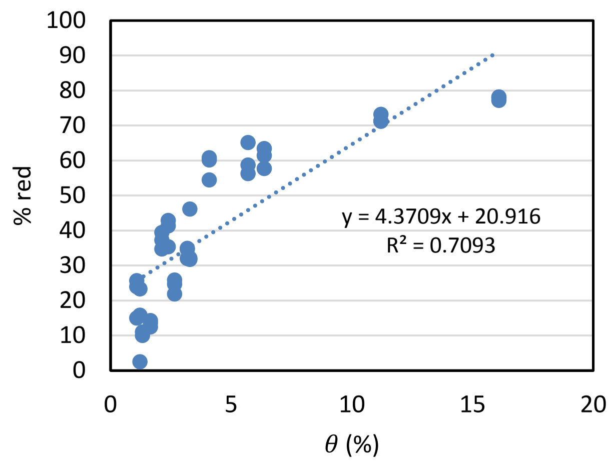
Figure 50 shows the linear regression results.



(a) 7-day



(b) 28-day



(c) 56-day

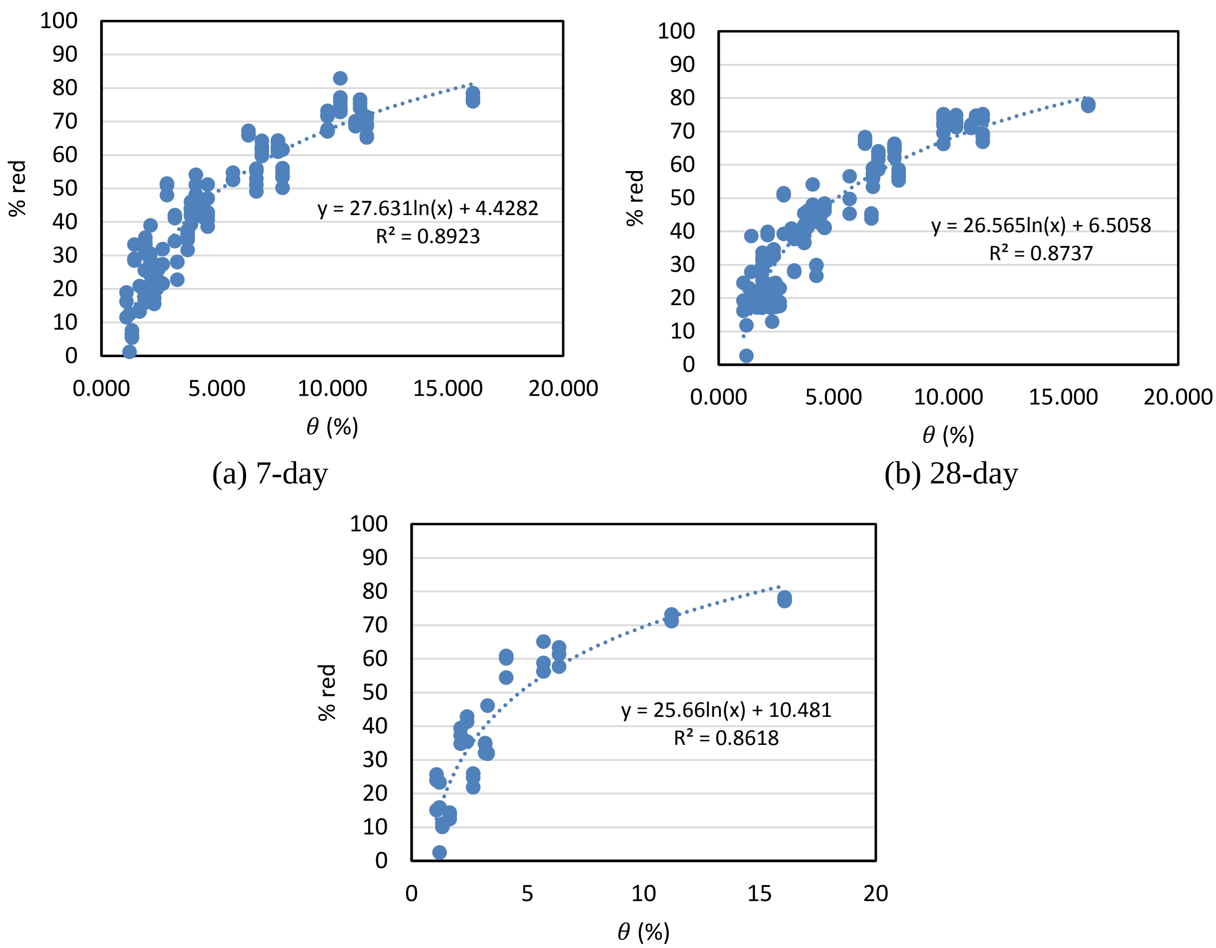
Figure 50. Linear Regression Results.

Figure 50 indicates a linear equation might not be the best equation to describe the correlation between θ and %red, as can be seen from the R^2 values. All three linear analysis had R^2 values lower than 0.85. The linear equations tended to overestimate the %red at higher binder contents.

To better fit the data, logarithmic models appeared to be the better choice. The logarithmic equation is assumed in Equation 6:

$$\%\,red = m \times \ln(\theta) + n \qquad \text{Equation 6}$$

Figure 51 shows the regression results using logarithmic models. The improved R^2 values suggest that it is more appropriate to use logarithmic equations to describe the correlation between the θ and %red.



(a) 7-day (b) 28-day (c) 56-day

Figure 51. Logarithmic Regression Results.

Two additional mixes (0.40_520_52BRY and 0.40_520_82BRY) were produced and tested to validate the correlation equations that shown in Figure 51. Table 32 presents the test results for these two mixes and the predicted %red with 99 percent confidence interval. Table 32 shows that the measured values for almost all of the cases are within the predicted bands. The higher the curing time, the better the prediction is. This again suggests that the strength of RAP-PCC is more related to the asphalt content in the system at the later stage of PCC curing.

Table 32. Additional Mixes Test Results.

Mix ID	Curing Time	Compressive Strength		% red	
		Mean (psi)	COV	Measured	Predicted
0.40_520_52BRY	7-day	2748	4.18	25.61	26.42–62.45
	28-day	3474	2.56	28.74	28.16–62.93
	56-day	3762	1.30	31.91	24.96–70.31
0.40_520_82BRY	7-day	2277	2.29	38.36	38.71–74.79
	28-day	2698	1.43	44.66	40.08–74.90
	56-day	3098	2.57	43.93	36.21–81.93

Generalized Correlation Equation

Compared to the variance contributed by the other factors (e.g., wc, cc, and θ), the %red did not vary too much with the curing time, shown in Figure 52. Therefore, a generalized correlation equation was generated by using all the available RAP-PCC data, regardless of the curing time, as shown in Figure 52. The generalized correlation equation, which is presented in Equation 7, has a R^2 value of 0.8576:

$$\%red = 26.455 \times \ln(\theta) + 6.2264 \qquad \text{Equation 7}$$

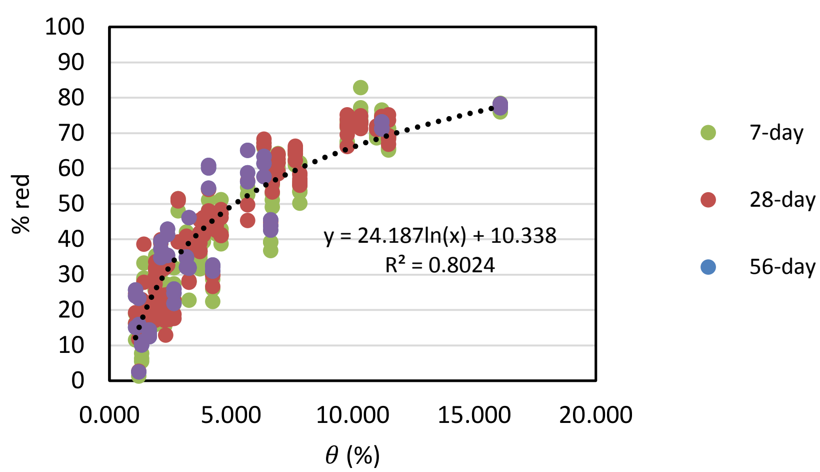


Figure 52. Comparison of Data at Different Curing Date and Generalized Correlation Equation.

Optimum RAP Replacement Estimated by the Generalized Correlation Equation

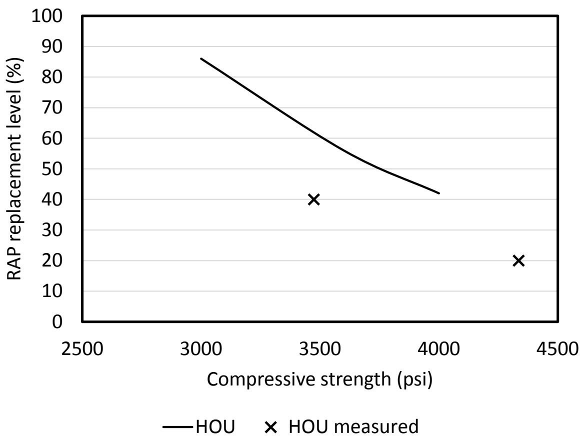
The optimum RAP replacement for different RAP types is estimated using the generalized correlation equation on the basis of different concrete class compressive strength requirement. The reference sample was selected as 0.40_520_REF, and its 56-day compressive strength was tested as 5525 psi in this study. Table 33 lists the optimum RAP replacement for different RAP types.

Table 33. Optimum RAP Replacement for Different RAP Type.

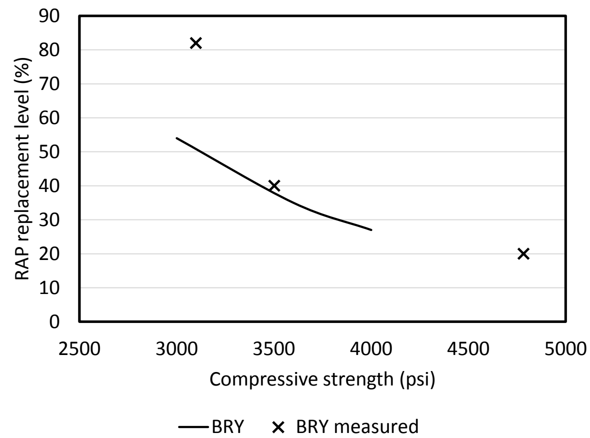
Concrete Class	Class A	Class B	Class C	Class E	Class S	Class SS
Required f'_c at 56 days by Item 421 (psi)	3000	2000	3600	3000	4000	3600
Allowable %red	45.7	63.8	34.8	45.7	27.6	34.8
Allowable θ calculated by the generalized correlation equation (%)	4.447	8.814	2.950	4.447	2.243	2.950
Allowable HOU replacement (coarse only) (%)	86	100	56	86	42	56
Allowable BRY replacement (coarse only) (%)	54	100	35	54	27	35
Allowable AMA replacement (coarse only) (%)	62	100	41	62	31	41
Allowable SA replacement (coarse only) (%)	66	100	44	66	33	44
Allowable BRY replacement (both coarse and fine) (%)	28	55	18	28	14	18

Error Analysis

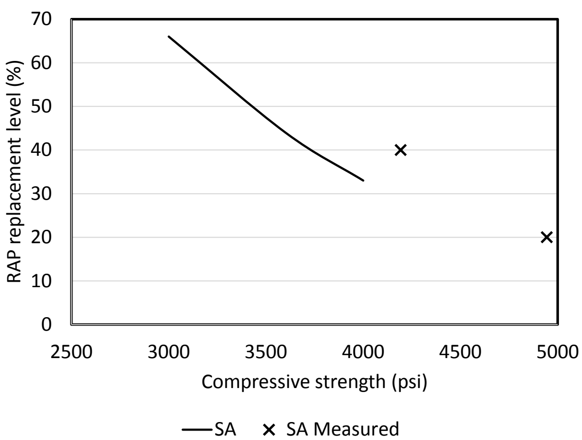
An error analysis was conducted by comparing the estimation in Table 33 with the real data obtained from actual tests in this study. Figure 53 plots the results. The solid lines are estimated RAP replacement using the generalized correlation equation, while the crossed points are data from the lab tests. Figure 53(a) presents the HOU RAP-PCC results. The figure shows the prediction slightly overestimated the RAP replacement level, which means adding HOU RAP into mixture induced more reduction than what the model predicted. This is very reasonable because HOU RAP contains lots of clumps (is presented in Chapter 3), which are considered the weak zone of the system. Figure 53(b) and (c) indicates that the generalized equation underestimated the BRY RAP-PCC strength (at high RAP replacement level) and the SA RAP-PCC strength. This matched the fact that both BRY_C and SA_C are good RAP sources with little clumps. For the combined use of coarse and fine RAP, Figure 53(d) suggests the predictions were overestimated RAP replacement level, and this finding can be explained as that the 0.40_520_BRY/BRY series had lower compressive strength than it should be due to a low w/c. When more water was introduced, the strength was increased (refer to 0.45_520_BRY/BRY results). Researchers concluded from Figure 53(d) that the use of fine RAP would induce more reduction in the strength than the addition of the coarse RAP that contributed to the equivalent binder volumetric fraction.



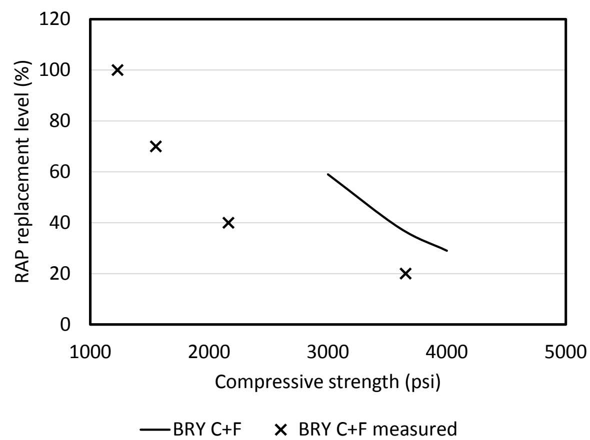
(a) HOU RAP-PCC



(b) BRY RAP-PCC



(c) SA RAP-PCC



(d) BRY/BRY RAP-PCC

Figure 53. Comparisons between Estimation and Lab Data.

In conclusions, the optimum RAP replacement estimation shown in Table 33 was largely based on the generalized correlation equation. Since the generalized correlation equation was generated based on all the available data covering (1) different w/cm, (2) different cementitious content, (3) different curing date, (4) different RAP replacement method (either using coarse RAP only or using both coarse and fine RAP), and (5) different RAP types, the predicted RAP replacement using the above-mentioned method may only be considered as an preliminary guess. However, this method might still be useful for low strength application (i.e., higher RAP replacement level), as the strength requirements for the low strength PCC may not be that rigorous. For a more rigorous and accurate prediction, case by case studies using the procedures that are similar with the class P concrete prediction are highly recommended. A more rigorous procedure to determine the optimum RAP replacement for low strength PCC is presented in Chapter 5.

CONCLUSIONS

One of the major tasks of this project was to validate the earlier findings on mechanical properties and durability of PCC containing coarse RAP. The 0.40_520_HOU, the 0.40_520_BRY, and the 0.40_520_AMA were evaluated through detailed testing. Regression models were developed to describe RAP-PCC mechanical properties with varying asphalt fractions. The model was validated by comparing the results for the 0.40_520_30BRY mix and the 0.40_520_BRY trend lines. The benefits of attaining dense combined aggregate gradation due to the replacement of certain percentage of coarse virgin aggregate by coarse RAP were demonstrated through the detailed analysis of the 0.40_520_BRY and 0.40_520_35SA mixes results. The following conclusions are made:

- Judicious use of coarse RAP with suitable gradation containing sufficient intermediate size particles (>50 percent) can ensure to make dense graded concrete not only because of the large amount of intermediate particles but also due to the fact that they are less flat and elongated. Presence of aged asphalt layer in the RAP aggregates provides some additional smoothness, which facilitates better flowability.
- Replacing virgin coarse aggregate by RAP in a typical PCC pavement mix has caused considerable reduction in compressive strength, MOE, and STS. The percentage reductions of flexural strength for all PCC mixes containing different types of RAPs remain the lowest among all other mechanical properties. The rate of reduction in compressive strength was the highest among the tested properties, while the rate of reduction in flexural was the lowest.
- RAP replacement exceeded 40 percent was considered to be impractical in field applications as percentage reduction of different strengths may not be allowed.
- In general, the rate of increase of compressive strength over time for RAP-PCC is lower than the reference mix. The rate of increase of flexural strength over time for RAP-PCC is lower for the 20 percent replacement but higher for the 40 percent replacement, compared to the reference mix.
- Both RAP compressive strength and flexural strength have strong linear relationship with GABVF, which enables the researchers to predict the properties based on regression equations.
- The 0.40_520_30BRY, the 0.40_520_40BRY, and the 0.40_520_35SA turned out to be dense graded RAP concrete mixes. The dense graded RAP concrete mixes showed better workability and mechanical properties compared to the other RAP concrete mixes made with gap graded RAPs (i.e., similar to gap graded virgin aggregates).
- ACI equations were modified to represent the RAP-PCC system and the modified equations were found to be effective to estimate MOE, MOR and STS from measured compressive strength. The methodology to determine optimum RAP replacement level and ideal RAP gradation was developed.
- Based on lab data, PCC concrete made of certain percentage of coarse RAP (≤40 percent RAP replacement) will not cause any durability issues related to permeability, freeze-thaw resistance, and shrinkage. The preliminary abrasion resistance data (ASTM C 779, Procedure A) shows that RAP-PCC mixes show comparable abrasion resistance property. However, a detailed study on measuring abrasion resistance property of various RAP-PCC mixtures containing RAP from various sources with varying level of replacement (≤40 percent) followed by performance evaluation through modeling is highly warranted to validate whether optimum RAP-PCC mixtures capable of satisfying the requirements of abrasion resistance/skid resistance for pavement applications.

In order to maximize RAP usage, the feasibility of using RAP to produce different classes of concrete of relatively low strength requirements has been evaluated. Data obtained from the experimental program in this project and the previously published research were analyzed. Statistical approaches were used to generate the correlation between the global asphalt binder volumetric fraction and the percent reduction in compressive strength. With this correlation, the optimum RAP replacement can be estimated. The major findings are summarized:

- The GABVF is a significant independent variable with respect to the dependent variable percent reduction in compressive strength, while the w/cm and cementitious content are insignificant independent variables.
- Logarithmic models are able to describe the relationships between the GABVF and the percent reduction in compressive strength. As the trend lines of GABVF versus percent reduction in strength for different curing ages did not vary much, a generalized correlation equation was generated regardless of the curing time of the specimens.
- The optimum RAP replacement for different RAP types was estimated by the generalized correlation equation. An error analysis showed the generalized approach can serve as an approximation (i.e., preliminary estimation) for determining RAP replacement, but more detailed and case by case study is needed for a project with specific RAP materials.

CHAPTER 3. MICROSTRUCTURE IN PCC CONTAINING RAP

RAP-PCC MICROSTRUCTURAL STUDY THROUGH ADVANCED TOOLS

Hardened concrete specimens covering different RAP-PCC mixes were sent to the National Petrographic Service Inc. in Houston for thin section preparation. Table 34 presents the information related to mix design, curing time, and sample selection. A blue dye was used during thin section (around 25 µm thickness) preparation to highlight the pores and cracks in cement paste matrix, aggregate particles, and ITZ. Therefore, pores and cracks were all highlighted by the blue color of the dye used for all the pictures provided. Researchers observed the thin sections under a transmitted light optical microscope (Figure 10) to obtain important microstructural information such as verifying the presence of agglomerated RAP particles (i.e., RAP clumps), ITZ characterization in terms of measuring and defining porosity, and size and distribution of calcium hydroxide (CH) crystals. This section presents a detailed discussion of the findings.

Table 34. Mix Design and Curing Time Information for the Samples Selected for Making Thin Section.

Mix ID	Curing Time	Sample Selection
0.40_520_REF	28 days	A representative slice of concrete sample taken from dedicated cylindrical (4" × 8") concrete specimen for petrographic examination after 28 days of moist curing
0.40_520_40HOU	28 days	Same as above
0.40_520_40BRY	28 days	Same as above
0.40_520_40SA	28 days	Same as above

Several 2 in. × 4 in. cylindrical specimens for RAP-PCC and reference PCC samples were made. An x-ray computed tomography (x-ray CT) [Zeiss, model Xradia 520 Versa, Figure 54] was used to take x-ray images of the hardened samples. X-ray CT is a very advanced nondestructive testing technique to scan any studied solid specimen and produce 3D images of all relevant features in the studied specimen through software reconstruction. Xradia 520 model has the capability to produce images with 1–5 micron resolution with a specimen of around 2 in. diameter. Indirect tensile loads were then applied to the selective samples (i.e., 0.40_520_REF, 0.40_520_40HOU, 0.40_520_40BRY, and 0.40_520_100BRY/100BRY) to induce cracks. Figure 55 presents a picture of the cracked RAP-PCC and reference samples.

Figure 54. Zeiss X-Ray Microscope Xradia 520 Versa.

Figure 55. Cracked RAP-PCC Samples.

The cracked samples were carefully wrapped and shipped to the National Petrographic Service Inc. for the thin section preparation. Table 35 presents the information on the thin section samples.

Table 35. Thin Section Information (Cracked Samples).

Mix ID	Curing Time	Sample Status when Sent Out
0.40_520_REF	14 day	Cracked
0.40_520_40HOU	14 day	Cracked
0.40_520_40BRY	14 day	Cracked
0.40_520_100BRY/100BRY	14 day	Cracked

Verifying the Presence of Agglomerated RAP

The presence of agglomerated RAP in different types of RAP-PCC samples were verified through thin section observations. The formation of agglomerated RAP happened when several RAP aggregate particles stick to each other due to the presence sticky asphalt binder around each RAP aggregate particle. The RAP agglomeration is a very common phenomena in the RAP stockpiles, especially when the ambient temperature is high. The presence of agglomerated RAP in RAP-PCC causes weak zones in concrete, which is one of the reasons of strength reduction in RAP concrete.

AMA RAP had significant amounts of agglomerations, while the particles from the HOU, BRY, and SA RAP sources appeared to be cleaner and more separated. However, under the microscope observation, HOU RAP also contains agglomerated RAP. One coarse HOU RAP particle, which appeared to be a single one from naked-eye observation, actually consists of several small RAP particles (Figure 56). Figure 56 shows a typical agglomerated particle in the 0.40_520_40HOU thin section sample. The coarse agglomerated RAP contains three intermediate sized particles (2–3 mm) and a relatively large particle (at the lower right corner of the picture) along with some fine RAPs (several hundreds of µm) and entrapped voids. Figure 57 and Figure 58 present a detailed observation of the asphalt layer within the agglomerated RAP particles (inside portion of the clump). Researchers observed the presence of fine aggregate particles and a large amount of voids (entrapped voids marked by blue dye) within the asphalt layer (Figure 57). In Figure 58, the thickness of the asphalt layer is around 500 µm (a magnified view), which contains several small fine particles. Because of the existence of small particles, the thickness of the asphalt layer varied significantly.

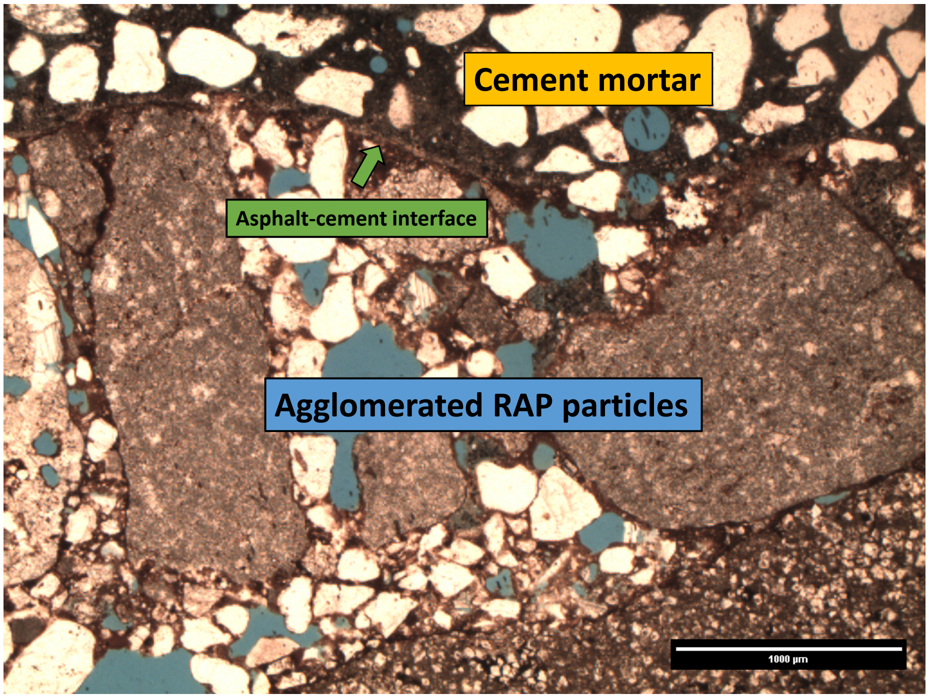


Figure 56. Agglomerated RAP Particles in the 0.40_520_40HOU Sample.

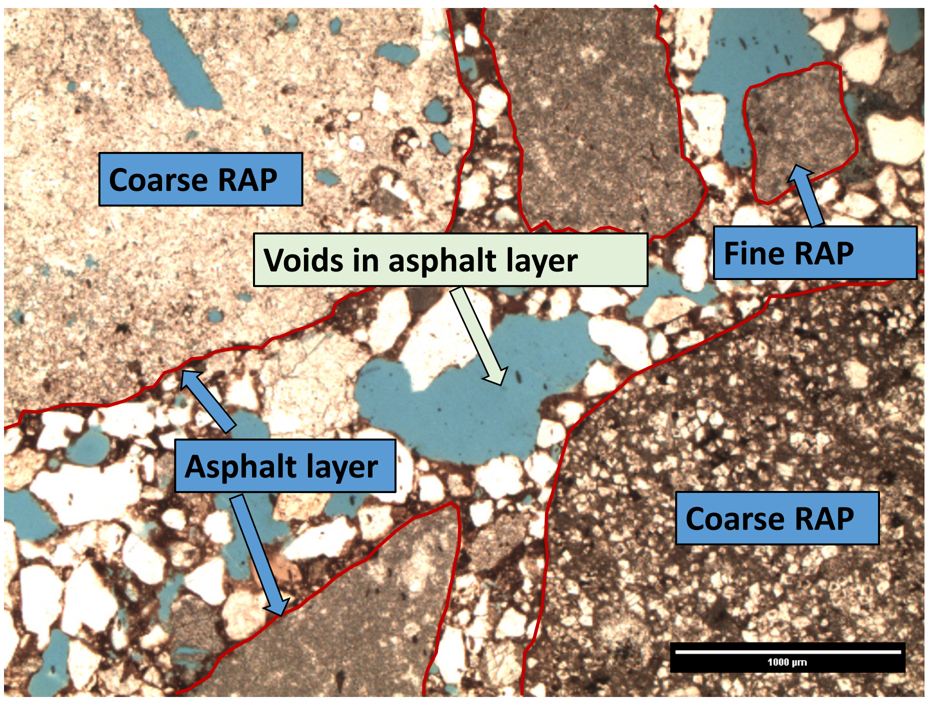


Figure 57. Another View of the Same Agglomerated RAP (0.40_520_40HOU).

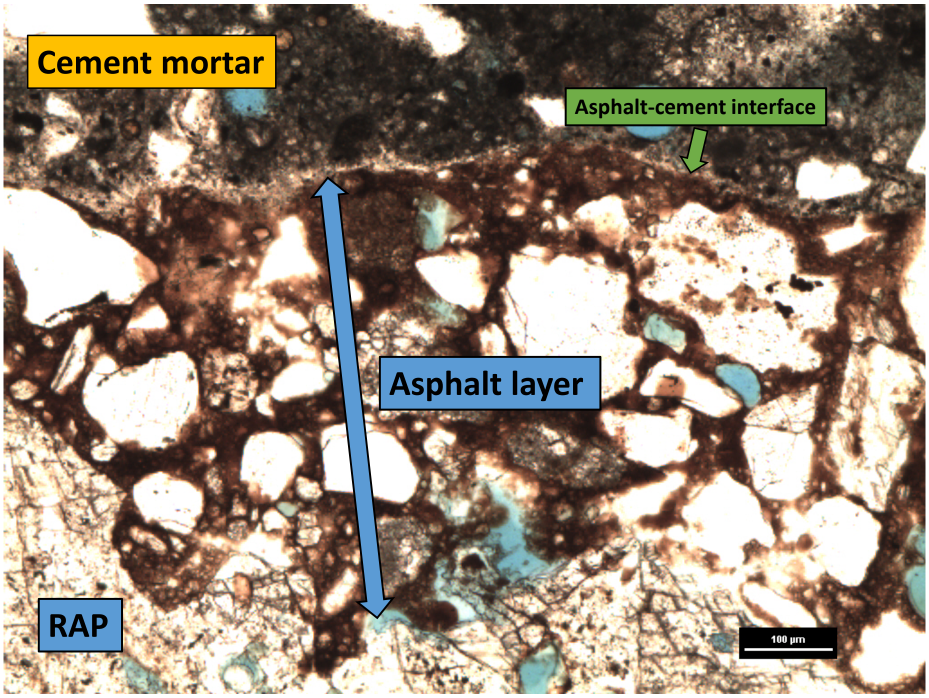


Figure 58. A View of the Thick Asphalt Layer of the HOU RAP (0.40_520_40HOU).

Figure 59 shows a RAP in the 0.40_520_40BRY thin section. Similar to the HOU RAP, some of the BRY RAP also contains asphalt layers with large amounts of fine particles. However, there are some RAP particles with a relatively thin and clean layer, as can be seen in Figure 60. During the observation of the 0.40_520_40BRY sample, no big clumps were observed.

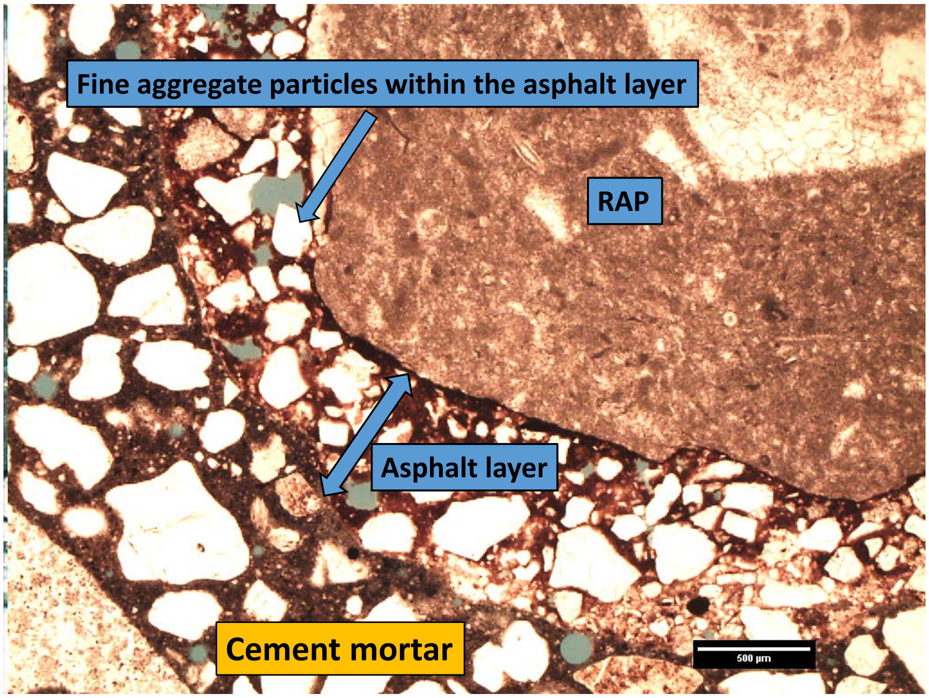


Figure 59. A View of the Asphalt Layer of the BRY RAP (0.40_520_40BRY).

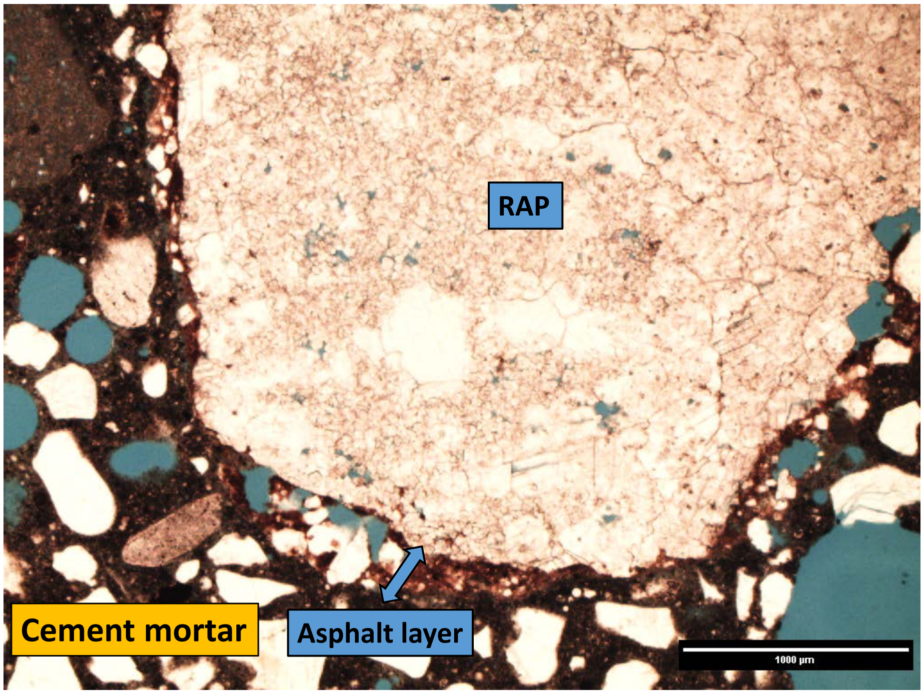


Figure 60. A Relatively Clean and Thin Asphalt Layer in the 0.40_520_40BRY (0.40_520_40BRY).

The 0.40_520_40SA was then observed. Unlike HOU and BRY cases, the SA RAP has very thin asphalt layer, as can be seen in Figure 61 and Figure 62. The asphalt layer is also cleaner with fewer fine particles. No big clumps existed in the 0.40_520_40SA samples.

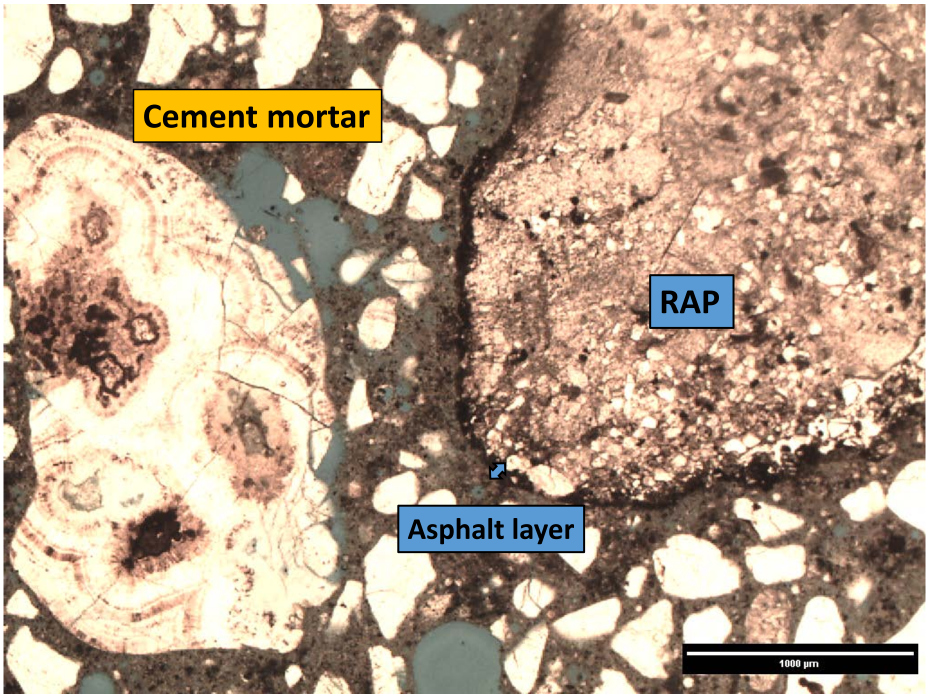


Figure 61. A Thin RAP Asphalt Layer in the 0.40_520_40SA Sample (0.40_520_40SA).

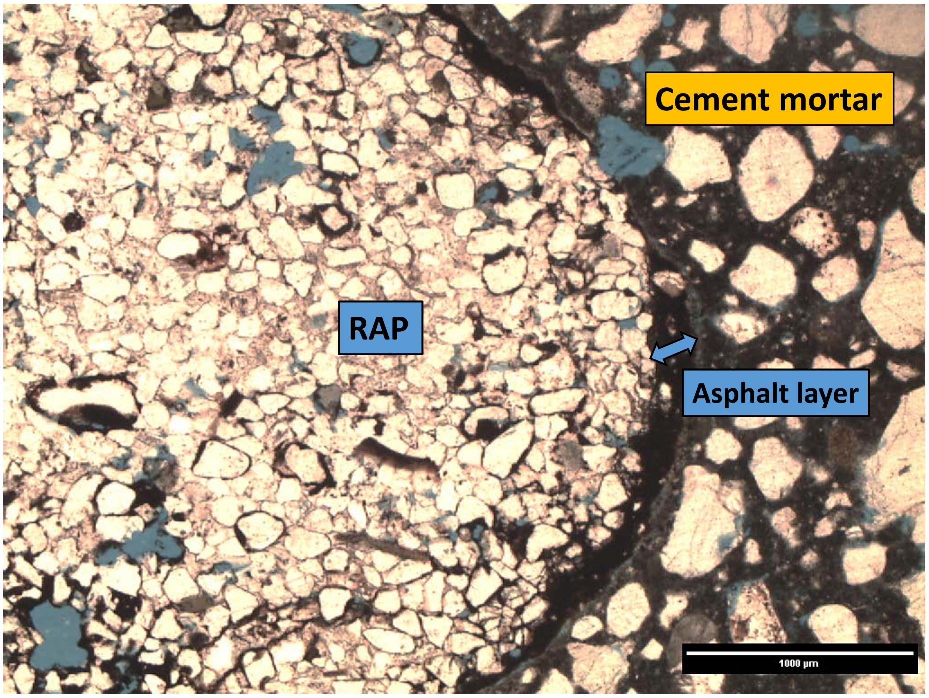


Figure 62. Another Thin RAP Asphalt Layer in the 0.40_520_40SA Sample (0.40_520_40SA).

ITZ Properties

In the normal concrete, the ITZ is a weak area where a crack is likely to propagate through. The weakness of ITZ is due to the following reasons (Bentur and Odler 1996; Maso 1980):

- The larger porosity.
- The larger CH crystals and its preferential orientation.

Based on the detailed observations on ITZ of different RAP hardened concretes, the ITZ of most of the RAP-PCC (especially those with higher levels of RAP replacement) is in general more porous than the ITZ of the reference concrete made of virgin aggregate, which can be shown in Figure 63 and Figure 64. Also, the ITZs in RAP-PCC show a higher degree of carbonation than that in reference concrete in general, which is another indirect evidence of porous nature of ITZ.

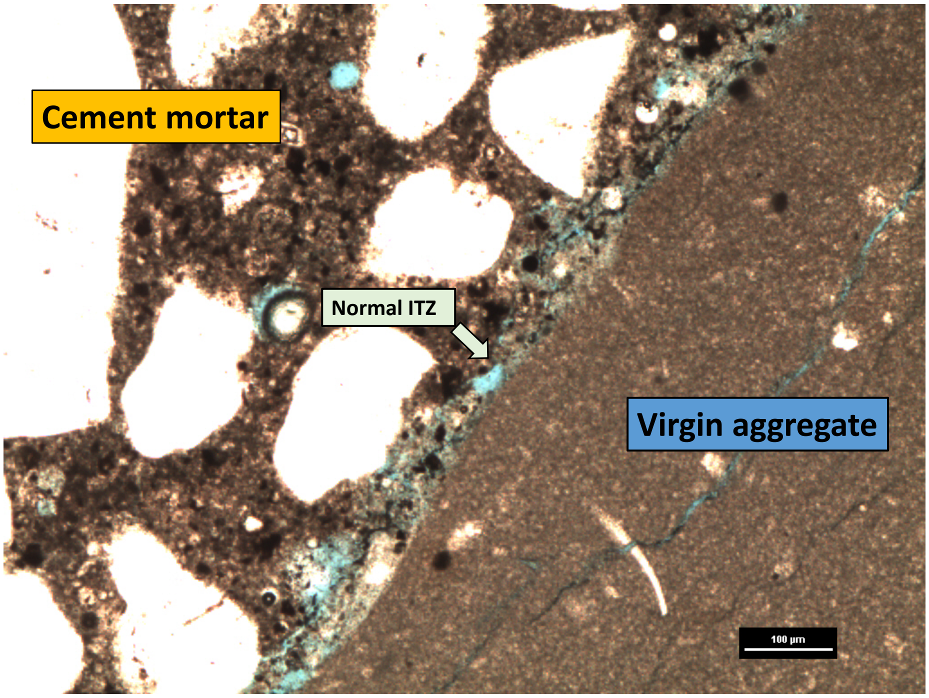
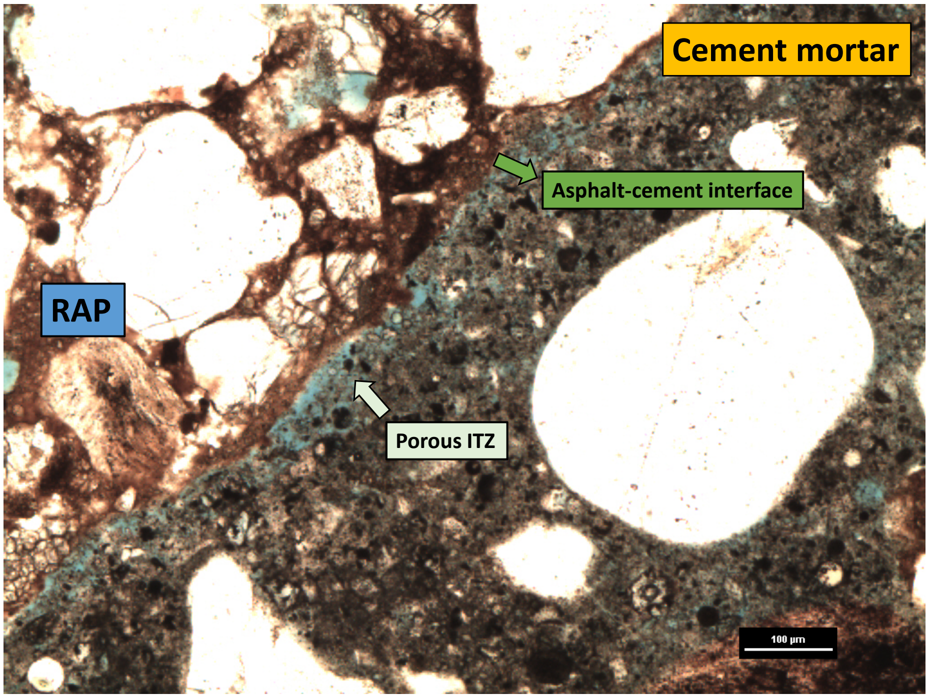


Figure 63. Normal ITZ in the 0.40_520_REF Sample.



Porous ITZ Represented by higher amount of blue dye impregnation. The higher the blue dye impregnation the higher the porosity is.

Figure 64. Porous ITZ in the 0.40_520_40HOU.

The scanning electron microscope (SEM) was used to further investigate the ITZ property of the RAP-PCC. Figure 65 shows a comparison of an ITZ between a RAP and cement (yellow dash line) and an ITZ between a virgin aggregate and cement (red dash line). It is clearly indicated that the ITZ between the virgin coarse aggregate and cement mortar is much denser and well-formed than the ITZ between RAP and cement mortar.

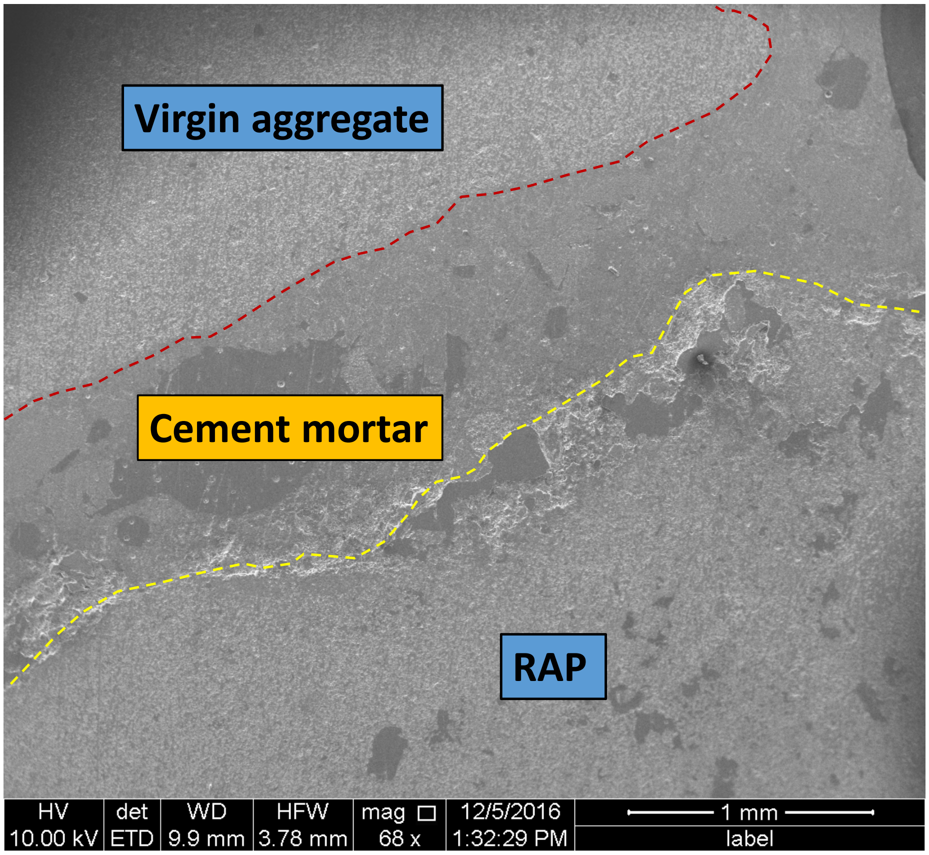


Figure 65. A Comparison of ITZs (0.40_520_40SA).

Size and Distribution of Pores by Petrographic Techniques

During the thin section observation, researchers observed that RAP-PCCs are in general more porous than the reference sample. A combined effect of both air voids and capillary pores in the cement paste and ITZ was considered to define the porous nature, which is described below:

- Presence of greater number of larger voids in the cement mortar of RAP-PCC samples – Figure 66 shows the air void distribution of the reference sample. The cement mortar contain well distributed air voids and most of them are entrained air that were purposely introduced to reduce freeze-thaw damage. Figure 67 is an image taken with the 0.40_520_100BRY/100BRY sample. Compared to Figure 66, the sizes of the air voids are bigger, and entrapped air can be found in a great number.
- Air voids exist in the thick RAP asphalt layer (Figure 57) – Figure 68 presents an extremely porous area in the RAP asphalt layer. Although it is not known that whether these air voids were original in the RAP material or they were introduced by default during the sample preparation due to the stripping of the asphalt, researchers note the thick asphalt layer is one of the weak points in the RAP-PCC system.
- Air voids within those big RAP clumps (Figure 56).
- Porous ITZ in the RAP-PCC (Figure 64).

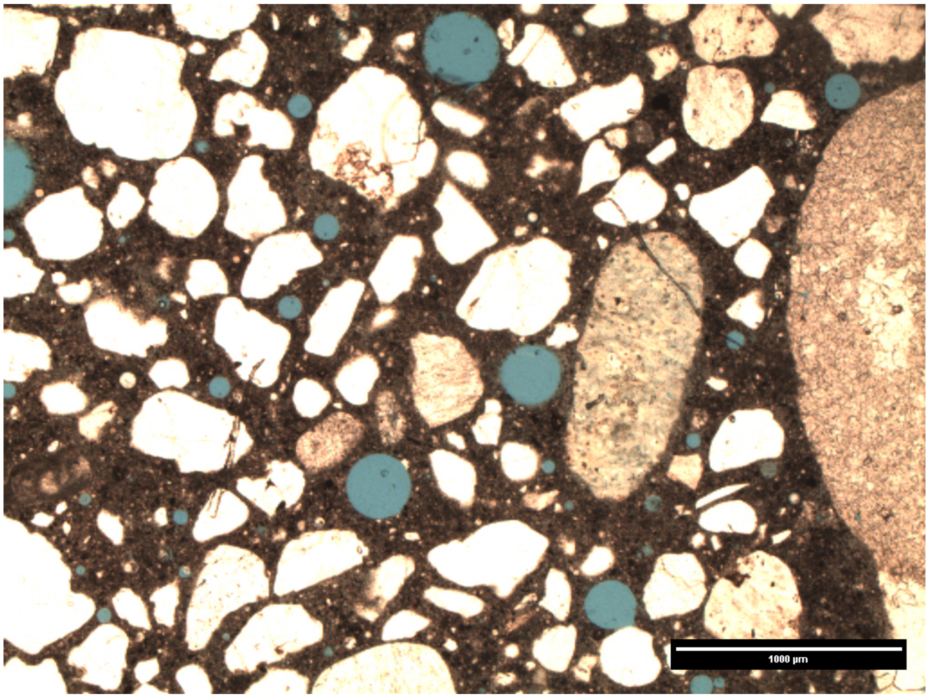


Figure 66. Air Voids in the 0.40_520_REF Sample.

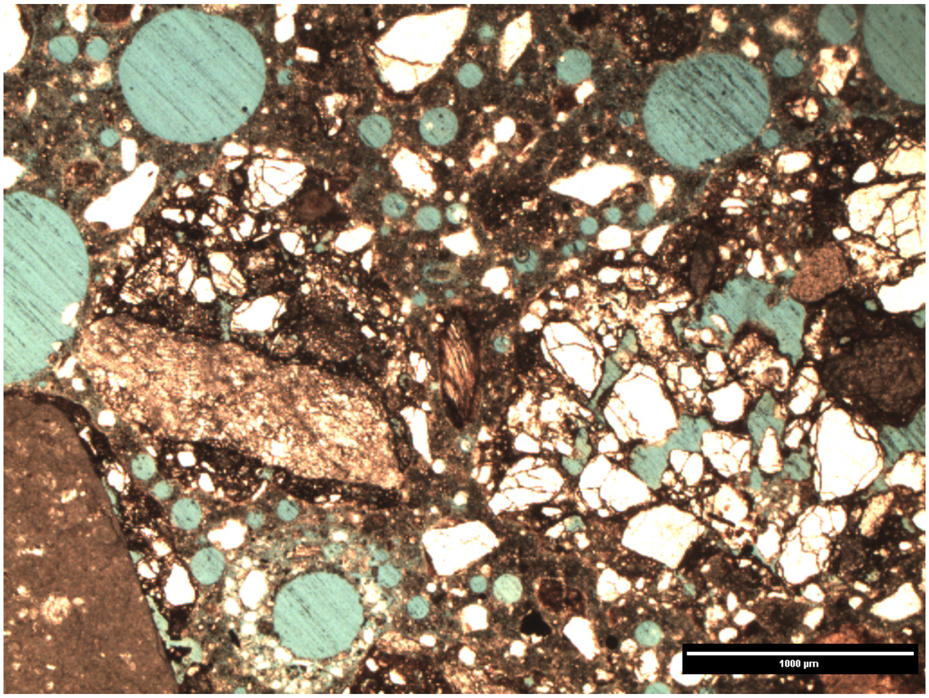


Figure 67. Air Voids in the 0.40_520_100BRY/100BRY Sample.

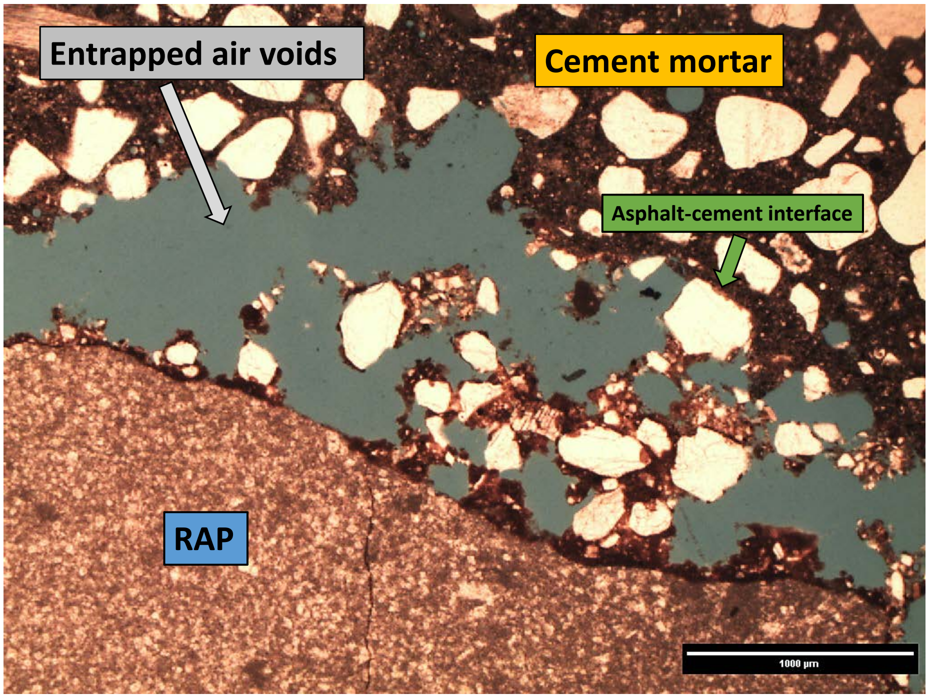


Figure 68. High Amounts of Air Voids in the Asphalt Layer in the 0.40_520_40BRY Sample.

Air Void Quantification of Un-cracked Samples by X-Ray CT

Before the samples were cracked, the percentage air void in the hardened concrete was estimated using the x-ray CT and the commercial software ORS Visual SI. The analysis procedures are:

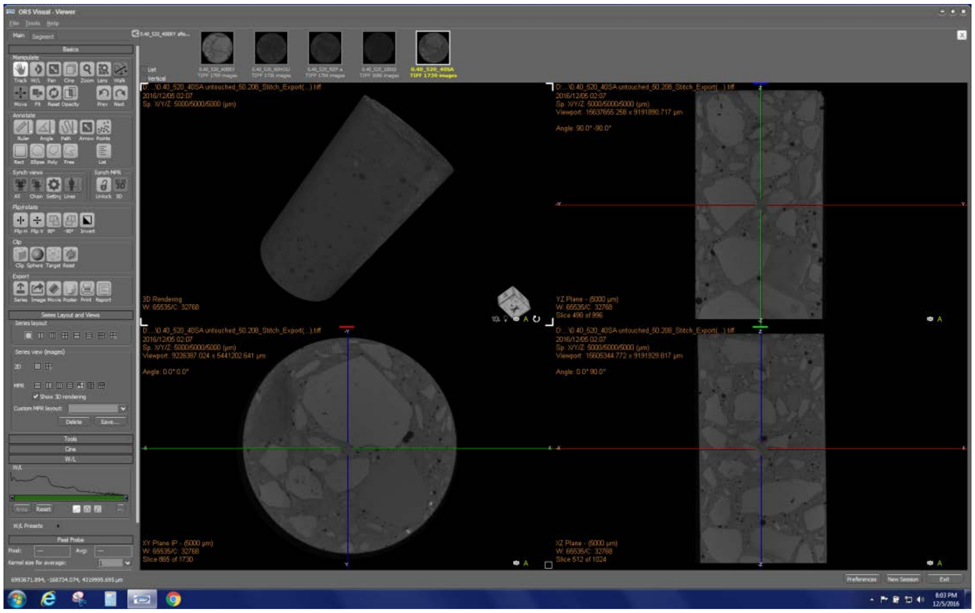
1. An un-cracked 2 in. × 4 in. concrete sample was mounted to the sample stage.
2. The scan parameters were determined after a trial and error process to make sure the best x-ray CT images were achieved. The voxel size was finally set as 53 µm. All the scan parameters were fixed for all of the samples.
3. After the x-ray scan was completed, 3D reconstruction technique was applied to obtain a 3D structure of the sample. The raw tiff image sequence was then saved.
4. The image sequence was then loaded in the commercial software ORS Visual SI. In order to remove the sample edge effect, the first 100 and the last 100 images from the image sequence were removed. Figure 69(a) shows a screenshot of the loaded sample.
5. The sample was then further trimmed and saved to ensure the full region of interest was within the sample (Figure 69(b) and Figure 69(c)).
6. The air void (black portion in the sample) was segmented by setting the grey value range. Although that this process is somewhat subjective, a good grey value threshold can be determined by comparing the segmented image (Figure 69(d)) with the original image (Figure 69(c)).
7. The volume percent air void for the trimmed sample was then calculated by the software.

Table 36 summarizes the percent air void for different RAP-PCC and the reference PCC samples.

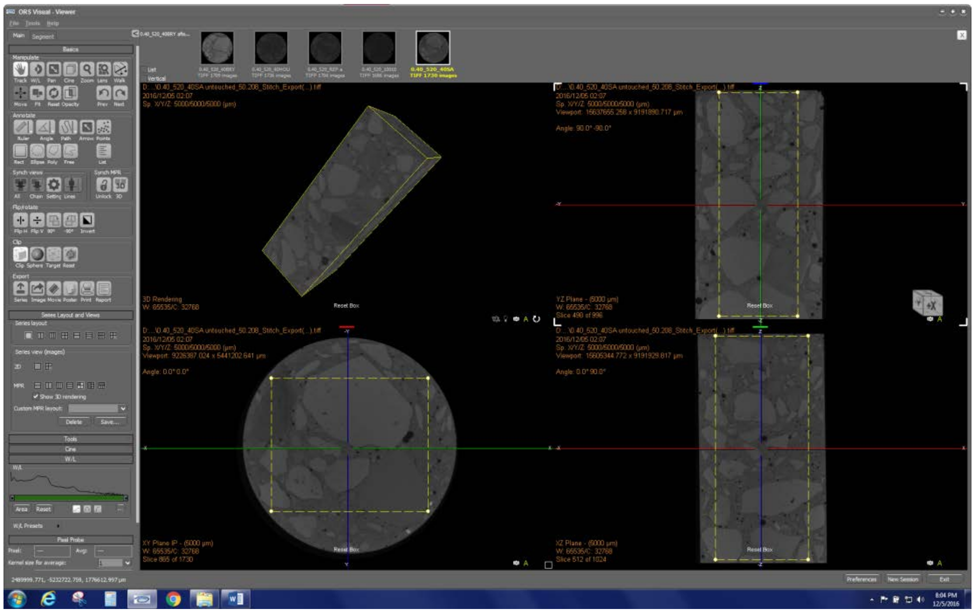
Table 36. Percent Air Void Calculations for Different RAP-PCC.

Sample ID	Grey Value Range	Air Void
0.40_520_REF	12068	1.19%
0.40_520_40HOU	13607	2.09%
0.40_520_40BRY	9084	2.42%
0.40_520_40AMA	8642	3.17%
0.40_520_40SA	10155	1.46%
0.40_520_100BRY/100BRY	12873	7.31%

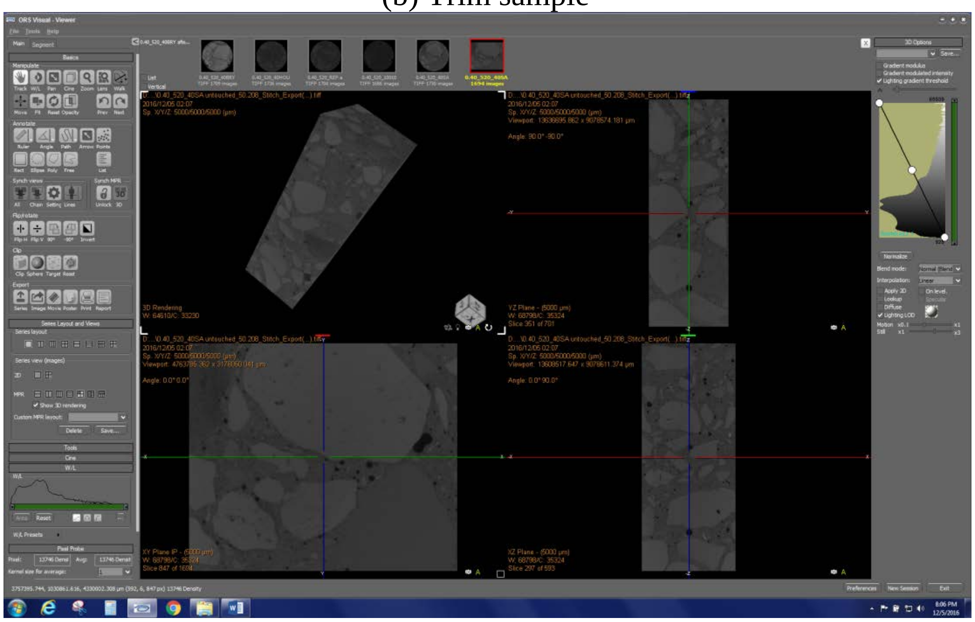
Table 36 indicates that RAP-PCC invariably has higher percentage air void than the reference PCC. The RAP-PCC containing 100 percent RAP aggregates had extremely higher amounts of air void compared to the other samples, which was considered one major reason of serious strength reduction. The 0.40_520_40AMA had higher percentage air void than the other samples with same RAP replacement level but different RAP type; the compressive strength 520_40AMA turned out to be lowest.



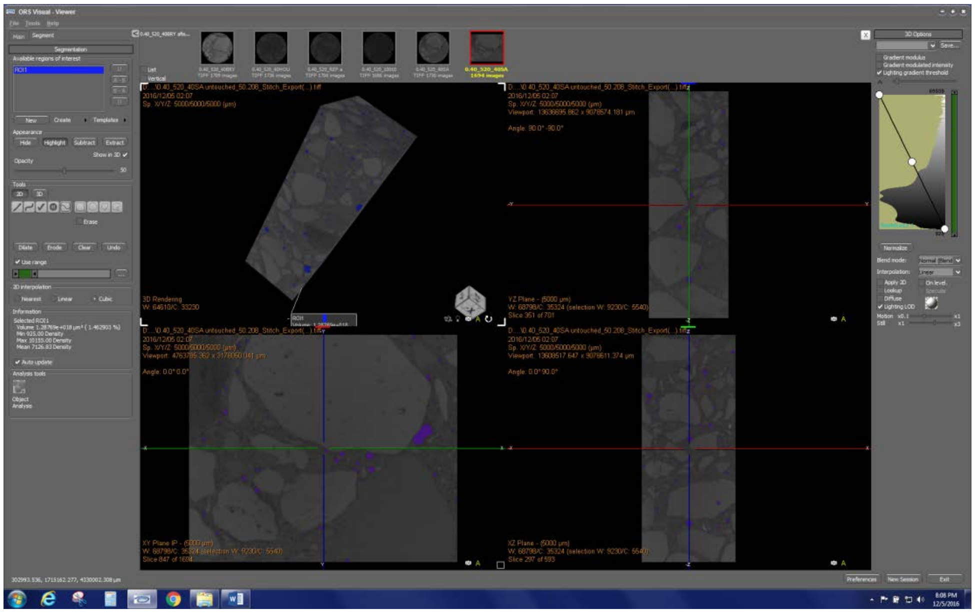
(a) Load image sequence



(b) Trim sample



(c) Save trimmed sample



(d) Segmentation and calculation

Figure 69. Procedures to Determine the Percent Air Voids in a Scanned Concrete Sample.

CH Size and Distribution

Based on detailed petrographic examinations, researchers concluded that the CH size and distribution in the RAP-PCC system appeared to be normal. Figure 70 presents the size and nature of distribution of the CH crystals in RAP-PCC under a microscope.

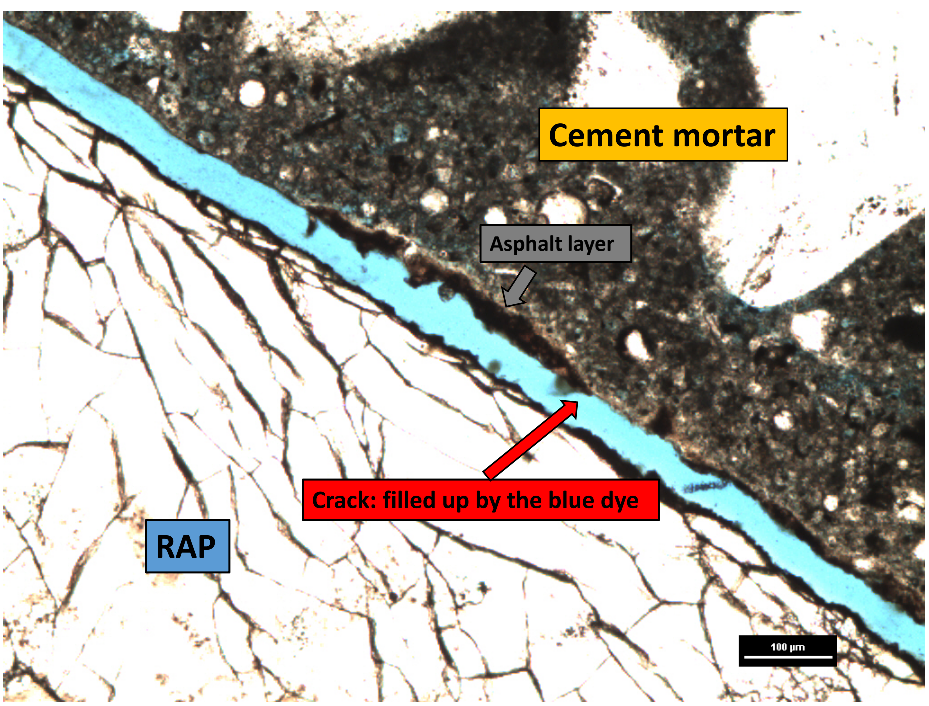


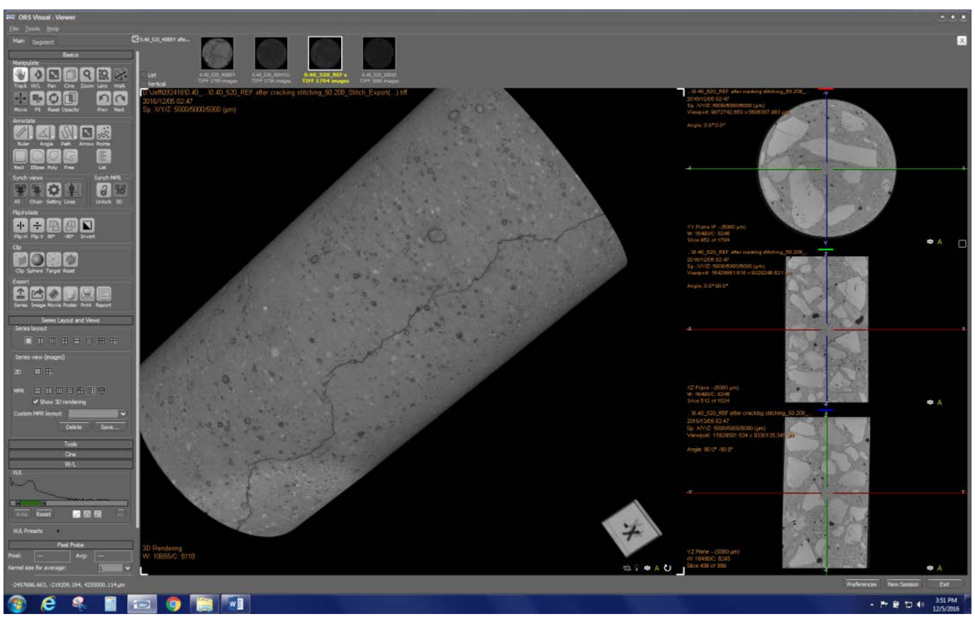
Figure 70. The Occurrences of CH Crystals at the Asphalt-Cement Interface, 0.40_520_40HOU Sample.

Crack Pattern in RAP-PCC

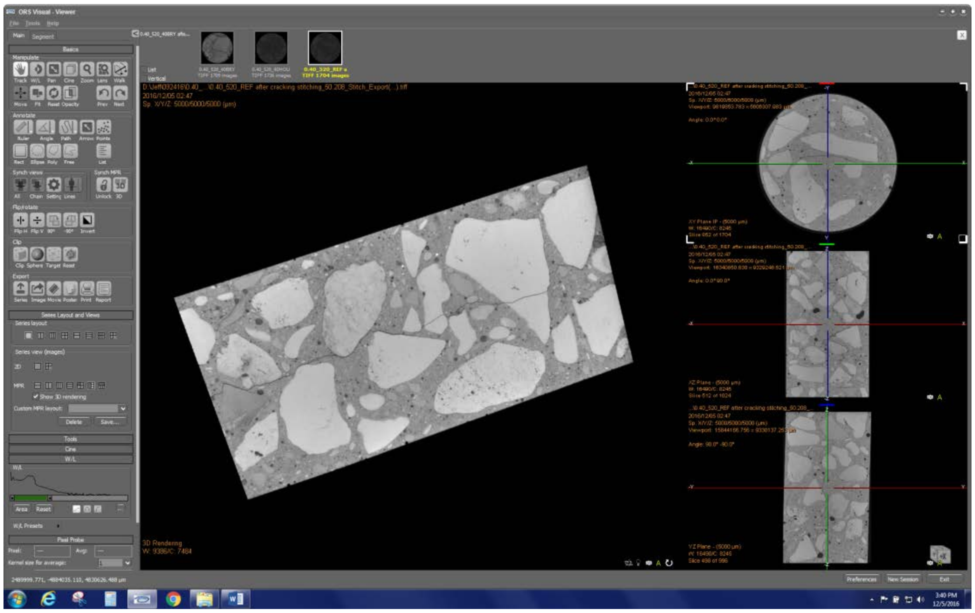
Crack pattern in RAP-PCC was investigated by X-Ray CT as well as petrographic techniques (thin section), which are described below.

X-RAY CT

The cracked samples (Figure 55) were scanned by the x-ray CT. The scans used the same scan recipe as that for the un-cracked samples. Figure 71 to Figure 74 presents the 3D structures of the cracked samples. Figure 71(a) shows a longitudinal crack in the 0.40_520_REF. The cross section (Figure 71(b)) indicates that the crack propagated through the aggregate. For a conventional PCC, when ITZs are good (in general ITZ between limestone coarse aggregate and cement paste is good) and aggregate is relatively softer or less hard (e.g., like the limestone used in this study), the aggregates break during testing and crack propagates through the aggregate instead of passing through ITZ. On the other hand, cracks always pass through the ITZ zone (specifically through the aggregate surfaces) in the RAP-PCC (Figure 72, Figure 73 and Figure 74), which indicates that the RAP and cement mortar interfaces are the weak zones in the concrete. Compared to a single longitudinal crack in 0.40_520_REF (Figure 71), all the RAP-PCC had multiple cracks (0.40_520_40HOU even had transverse crack, Figure 72). Multiply cracks are often the indication of a higher toughness and ductility. Besides, Figure 72 clearly shows a HOU RAP clump in the sample, and the cracks tended to initiated and passed through the clumps. This again proved that the RAP slump is the weak zone in the RAP-PCC system and should be strictly controlled. For the 0.40_520_100BRY/100BRY sample in Figure 74, very high porosity was observed.

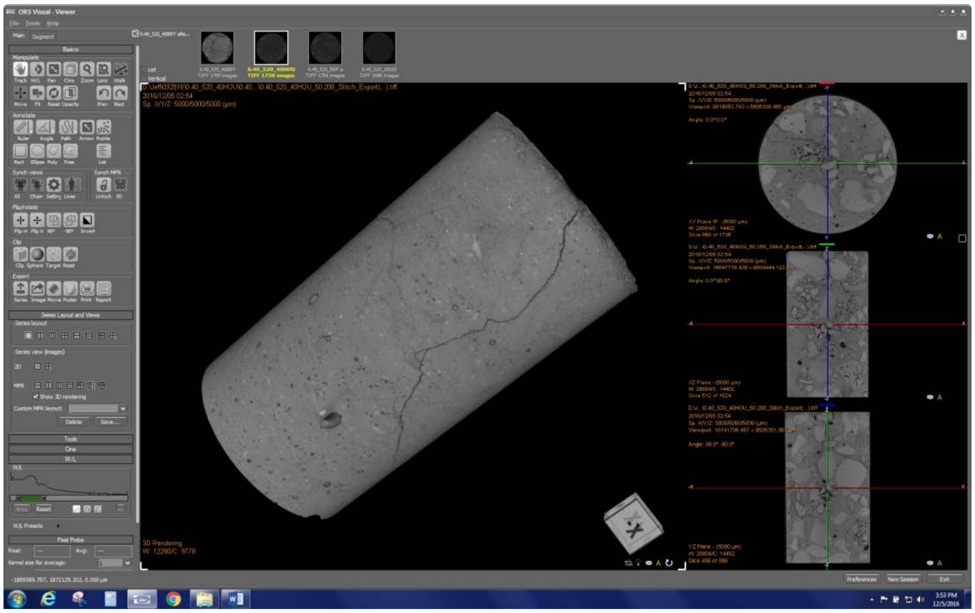


(a) Entire view

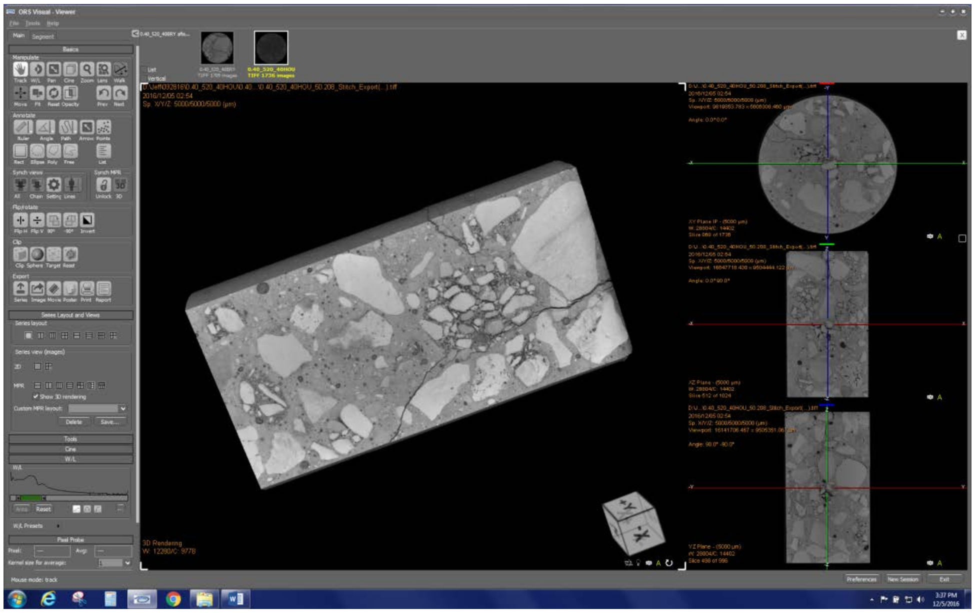


(b) Cross section

Figure 71. 3D Images for Cracked 0.40_520_REF.

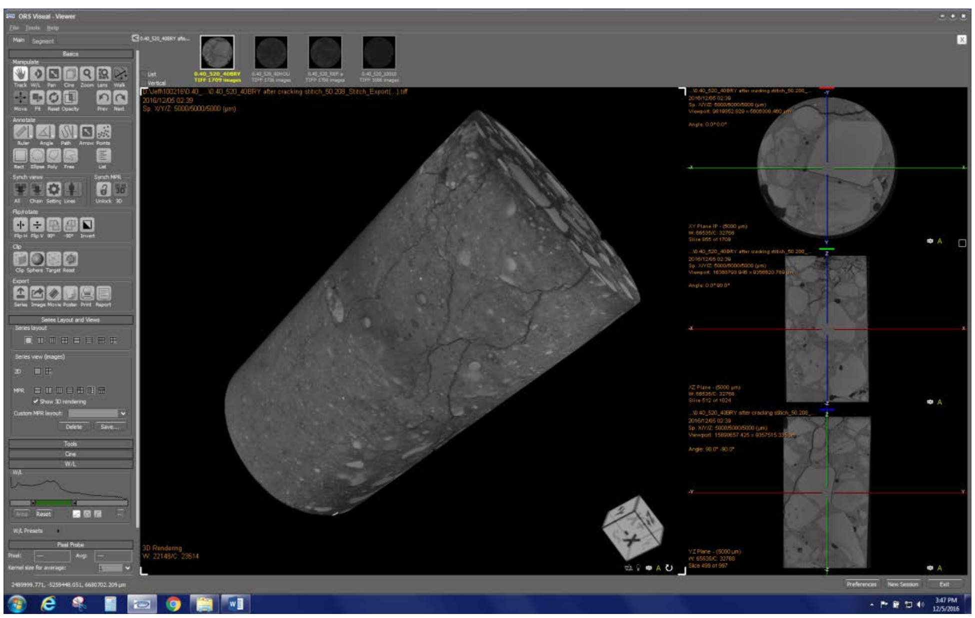


(a) Entire view

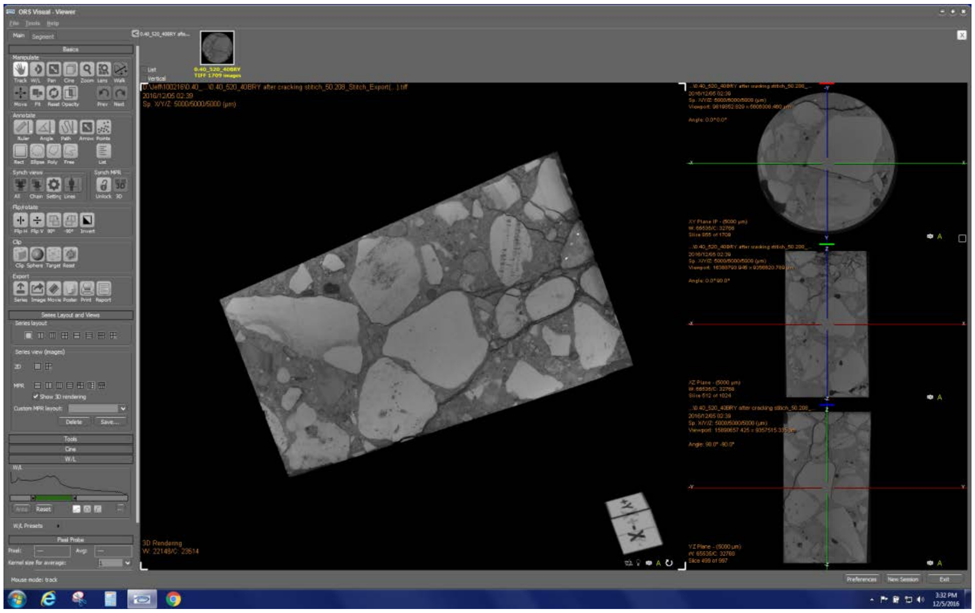


(b) Cross section

Figure 72. 3D Images of Cracked 0.40_520_40HOU.

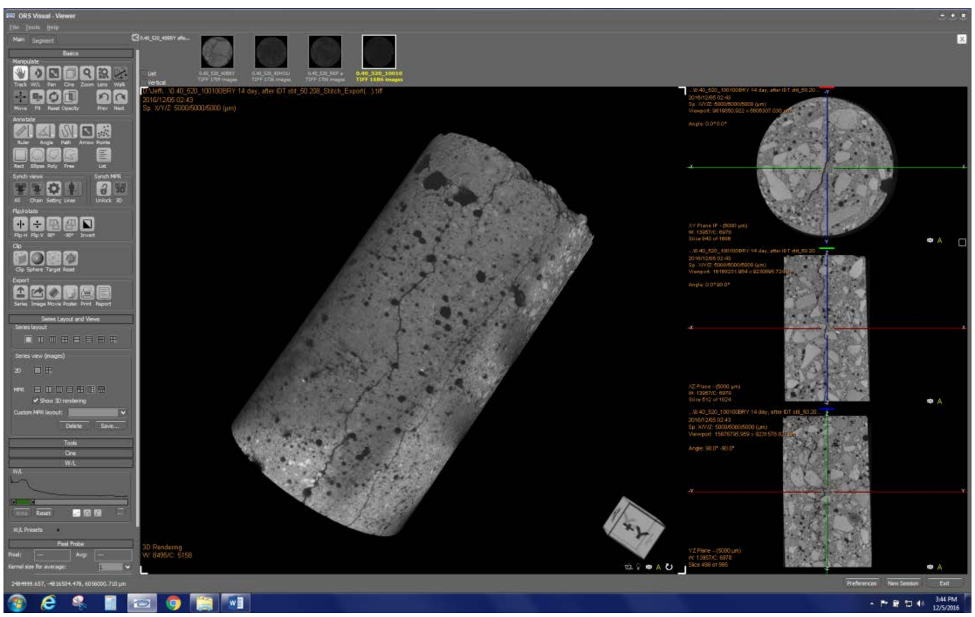


(a) Entire view

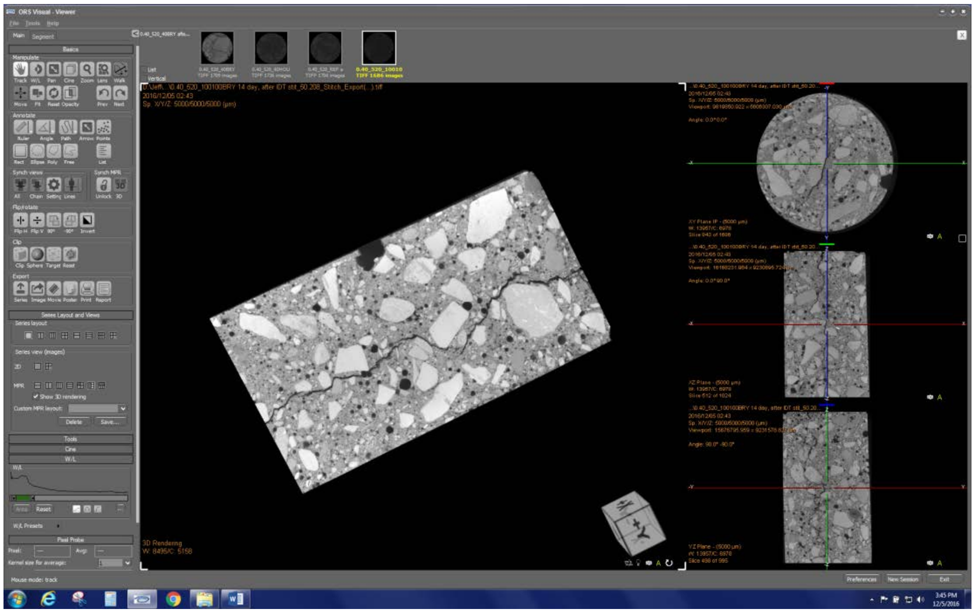


(b) Cross section

Figure 73. 3D Images of Cracked 0.40_520_40BRY.



(a) Entire view



(b) Cross section

The black small circular portions represent air voids.

Figure 74. 3D Images of Cracked 0.40_520_100BRY/100BRY.

Thin Section

As soon as the thin sections were received, the crack patterns were studied under the optical microscope to investigate the failure mechanism in RAP-PCC. Based on a detailed thin section observation, the following findings on the failure mechanism were obtained:

- Asphalt cohesive failure is the primary failure mechanism in the RAP-PCC system. This can be verified by Figure 75 and Figure 76.
- The big RAP clumps in the PCC system causes weak zones due to their high porosity and high asphalt binder content. Figure 77 shows a typical crack passing an agglomerated RAP.
- As asphalt cohesive failure is the primary failure mechanism in RAP-PCC, the ITZ properties of RAP-PCC are relatively less critical in the RAP-PCC because the RAP-PCC ITZ properties do not differ considerably in terms of CH size and distribution. However, the porous nature of ITZ in RAP-PCC plays some role for crack propagation through the ITZ.
- The extremely higher amounts of pores in PCC with high RAP replacement level made crack initiate and propagate much more easily, which was demonstrated in Figure 67.

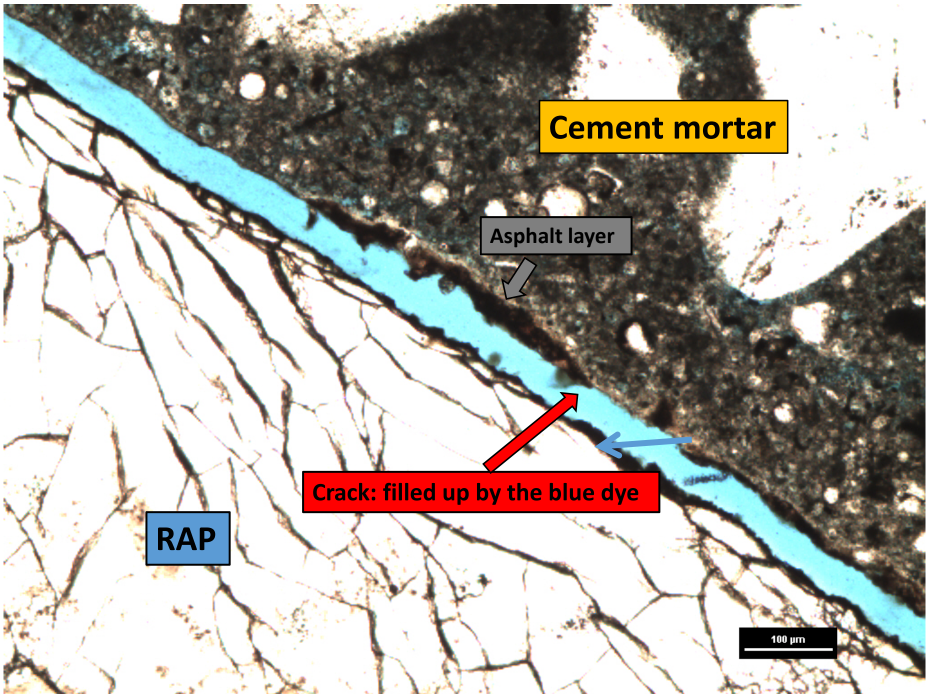


Figure 75. An Example of Asphalt Cohesive Failure (0.40_520_40HOU) (i.e., Crack Passing through the Asphalt Layer).

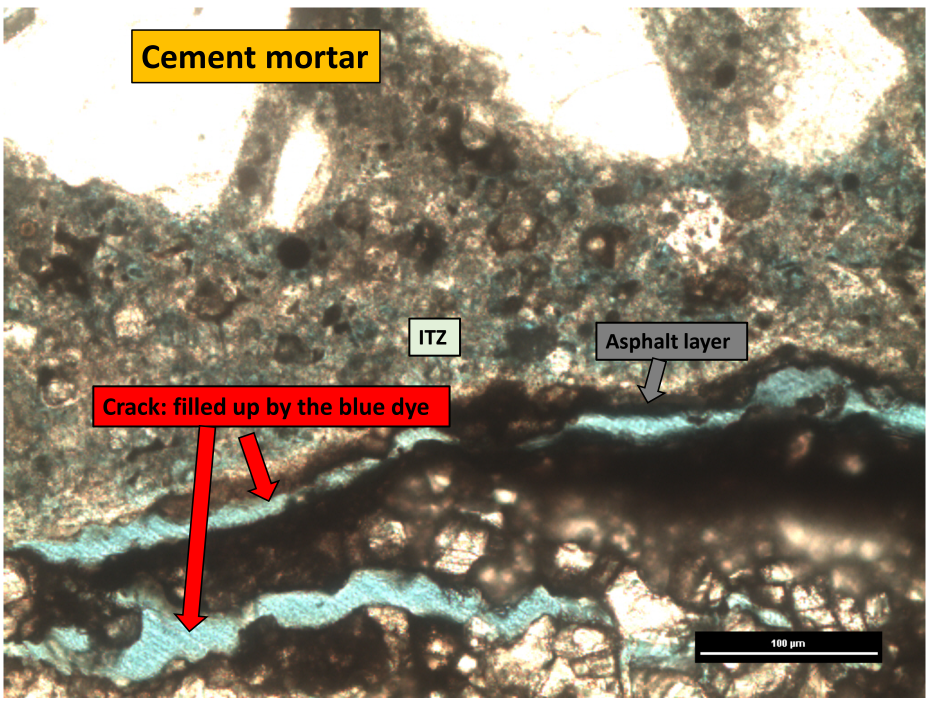


Figure 76. A Close View of the Asphalt Cohesive Failure (0.40_520_40HOU) (i.e., Crack Passing through the Asphalt Film).

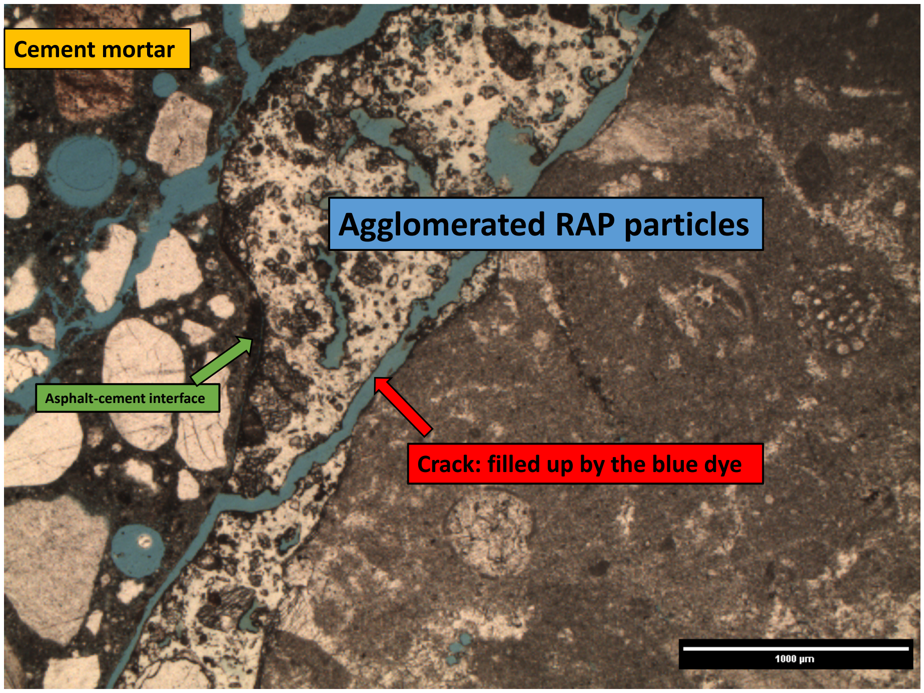


Figure 77. Crack Propagates through the Agglomerated RAP Particle (0.40_520_40BRY, 25×).

EFFECTS OF RAP ON CEMENT HYDRATION

The effects of RAP on cement hydration were investigated. A microcalorimeter (produced by Omnical Inc.) was used to perform the heat hydration study. Figure 78 shows a picture of the microcalorimeter. Because of the limitation of the sample size, no coarse RAP was used and only the cement mortars containing fine RAP and virgin sand were tested. To remove the effects of fine aggregate size on cement hydration, both fine RAP and virgin RAP were obtained by only collecting particles passing No. 16 sieve but remained on No. 30 sieve. The mortar mix designs 0.40_520_REF-M and 0.40_520_RAP-M adopted those of the 0.40_520_REF and 0.40_520_100BRY/100BRY (without any coarse aggregate or coarse RAP), respectively. The heat hydration tests were conducted based on the following steps:

1. Set the microcalorimeter chamber temperature at 20°C and wait for the temperature equilibrium.
2. Batch the dry ingredients that can make 20 cm^3 mortar sample.
3. Prepare the right amount of water and add the water into the dry mixture.
4. Mix the ingredients with a wood stir bar for 2 minutes.
5. Transfer the mortar mixture to the small glass jar immediately and measure the sample weight.
6. Wait until 5 minutes after mixing, then put the glass jar in the microcalorimeter and start the test.
7. Both the 0.40_520_REF-M and the 0.40_520_RAP-M strictly followed the above procedures to ensure consistency.

Figure 79 shows the preliminary results based on heat of hydration measurements. Figure 79 shows that the mortar sample made of virgin fine aggregate had a slightly higher first peak than the mortar made of fine RAP. However, the difference in heat generation for the first peak is not considerable and the curves almost superimposed to each other after around 30 minutes. Further work is needed to verify whether slightly smaller heat generation during the first peak formation for the RAP mortar is responsible for any measurable lower degree of hydration.

Figure 78. The Microcalorimeter Used in This Study.

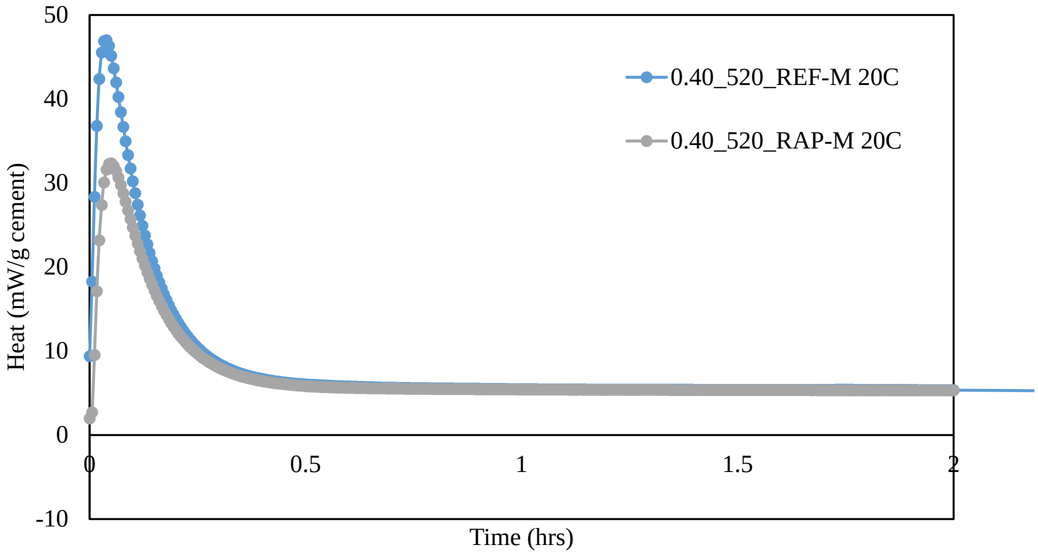


Figure 79. Heat Hydration Curve.

CONCLUSIONS

An evaluation of the microstructures and crack propagation in RAP-PCC was conducted. Four advanced tools, namely the optical microscope, x-ray CT, SEM, and the microcalorimeter, were used in a combined manner to investigate the mechanisms related to chemical interactions between asphalt and cement hydration and the mechanisms responsible for the mechanical properties observations in this study. The major findings from the investigation are:

- Based on the findings from the RAP-PCC thin section examination, the presence of a clean asphalt layer (i.e., asphalt layer alone without any other particulate materials) around RAP particles was not observed in any of the studied RAP materials. In general, the asphalt layer contains varying amounts of fine aggregates and air voids.
- The presence of RAP clumps (i.e., agglomerated RAP particles) in all the studied RAP materials is a common feature. The agglomerated RAP particles appeared to be a single particle in naked eye but their agglomerated nature was clearly visible under a microscope.
- Adding RAP into PCC yielded porous ITZ, but the effects on the size and nature of distribution of CH crystals in the ITZ area is minimal.
- The major weak point of the RAP-PCC system is the asphalt. Asphalt cohesive failure (i.e., crack easily propagate through the asphalt layer around the RAP particles) is the major failure mechanism. The presence of RAP clumps is also found to be other weak zones in RAP-PCC and has some connection depending on the degree of clump formation with the reduction in strengths.
- The presence of RAP has caused higher amounts of air voids in the studied RAP-PCC mixtures compared to the reference PCC sample.
- The mortar sample made of virgin fine aggregate had a slightly higher first peak than the mortar made of fine RAP in the heat of hydration curve.

CHAPTER 4. EVALUATION OF RAP-PCC PAVEMENTS

The performance of the concrete mixes made of RAP aggregate was evaluated through critical stress analysis by applying suitable models. A pavement slab design was performed through TxDOT approved design tools. The positive impacts of using RAP in PCC pavement were investigated by an online life cycle assessment in this chapter.

CRITICAL STRESS ANALYSIS FOR PAVEMENT DESIGN

The critical stress analysis was conducted by using the pavement finite element software ISLAB 2000, developed by Applied Research Associate. A typical PCC structure in Texas was used in the simulation (shown in Figure 80). For the PCC slab, the 0.4_520_HOU and 0.4_520_BRY mixes were used in the simulation in order to have a performance comparison between PCC pavement mixes made of different RAPs. All of the input parameters required for PCC slab performance prediction were directly obtained from the lab tests in Chapter 2. For the base and subgrade, some of the required input parameters were collected from relevant literature, and the remaining parameters were assumed based on the experience of the research group with proper justification. Table 37 shows the material property inputs for different layer. The subgrade model used in the simulation is a Winker model, and the modulus of subgrade reaction (k value) is computed using the correlation equation in the AASTHO 1993 guide (AASTHO 1993):

$$k = \frac{M_R}{19.4} = \frac{30000 \text{ psi}}{19.4} = 1546 \text{ pci} \qquad \text{Equation 8}$$

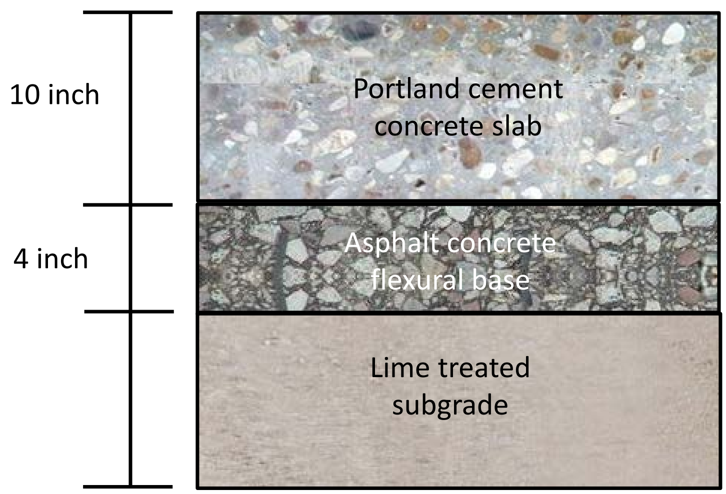


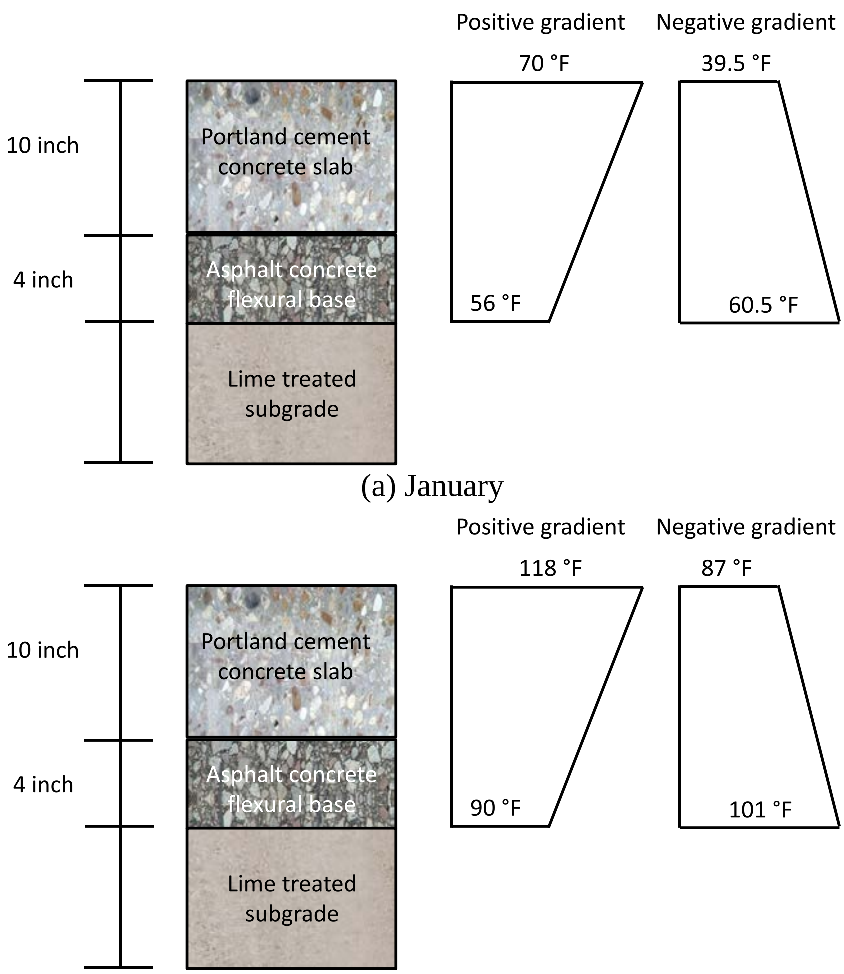
Figure 80. A Typical PCC Pavement Structure in Texas.

Table 37. ISLAB 2000 Material Property Inputs.

Structure		Modulus (×106 psi)	Poisson's Ratio	Unit Weight*(pci)	CoTE (10-6/F)
PCC slab	0.40_520_REF	4.779	0.151	0.0851	4.463
	0.40_520_20HOU	4.198	0.162	0.0846	4.847
	0.40_520_40HOU	3.554	0.176	0.0833	4.950
	0.40_520_20BRY	4.164	0.180	0.0847	5.085
	0.40_520_40BRY	3.490	0.190	0.0833	5.670
Asphalt concrete flexural base		0.3	0.35	0.0868	13.010
Lime treated subgrade		0.03 (equals to k=1546 pci)	N.A	N.A	N.A

* Unit weight of hardened concrete was measured using ASTM C138

In order to perform the temperature related analysis, typical representative pavement temperature profiles were assigned to the pavement structure based on experience and literature review. Figure 81 shows the pavement temperature profile representing both positive gradient and negative gradient conditions in January and July.



(a) January

(b) July

Figure 81. Typical Pavement Temperature Gradients.

A typical slab dimension with 15 ft in longitudinal direction and 12 ft in transverse direction was used. The mesh size was selected as 2 in. A square loading (9000 lb) that induced 82.06 psi pressure in the middle of the slab was applied. Figure 82 shows a picture of the ISLAB interface.

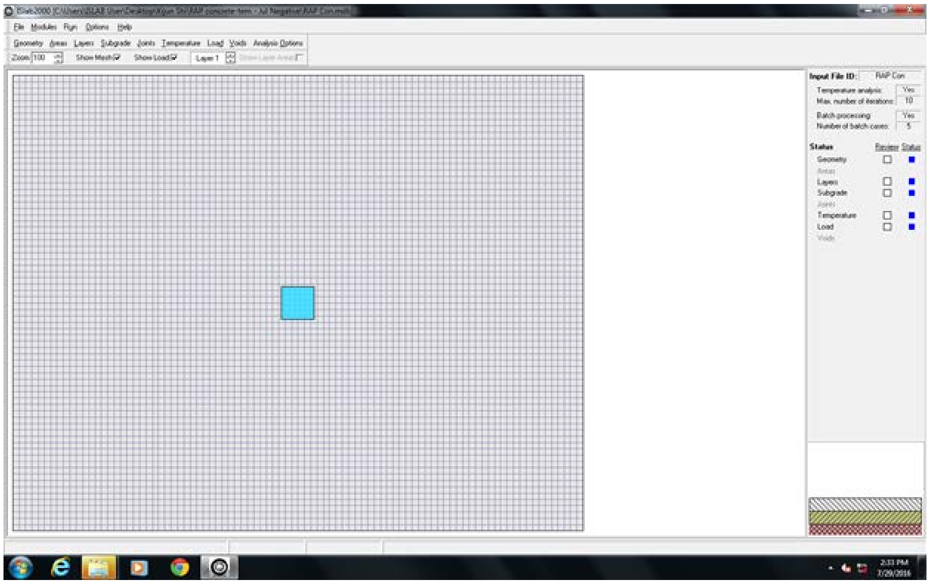
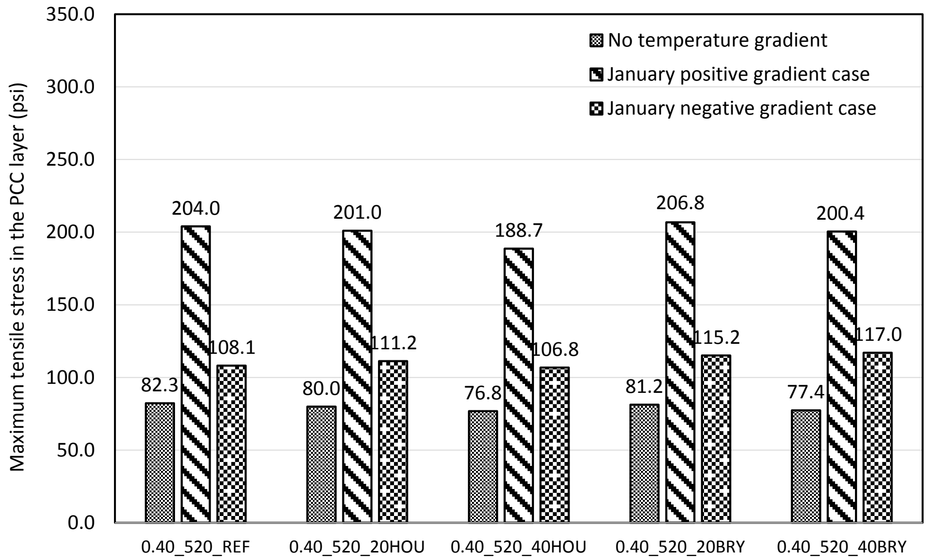
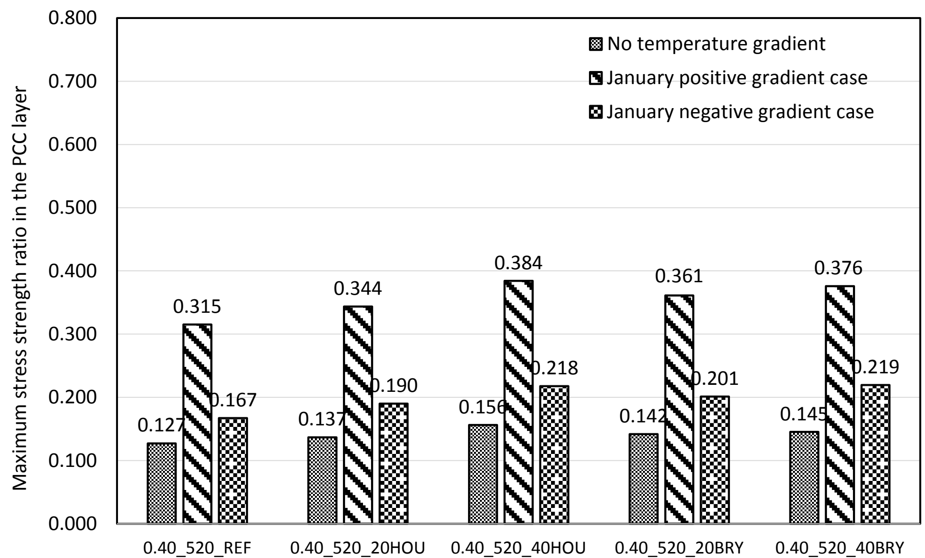


Figure 82. ISLAB 2000 Interface.

Figure 83 and Figure 84 plots the maximum tensile stress and the maximum stress to strength ratio in the PCC slab. The figures show that if there is no temperature gradient or a positive temperature gradient in the pavement, the RAP concrete slab would have smaller tensile stress than the reference concrete slab for most cases, which is likely due to a combined effect of lower modulus and higher CoTE of the RAP concrete. However, when a negative temperature gradient is applied, the tensile stresses for the RAP concrete slab become slightly higher that that at reference concrete because of the higher CoTE of the RAP concrete materials. The stress/strength ratio was calculated as the ratio between the maximum tensile stress and the flexural strength for all the studied concrete mixes. The cases for PCC slab made of RAP concrete mixes show slightly higher stress/strength values than the case of PCC slab made of reference mix, which is largely because the concrete containing RAP had reduced flexural strength.

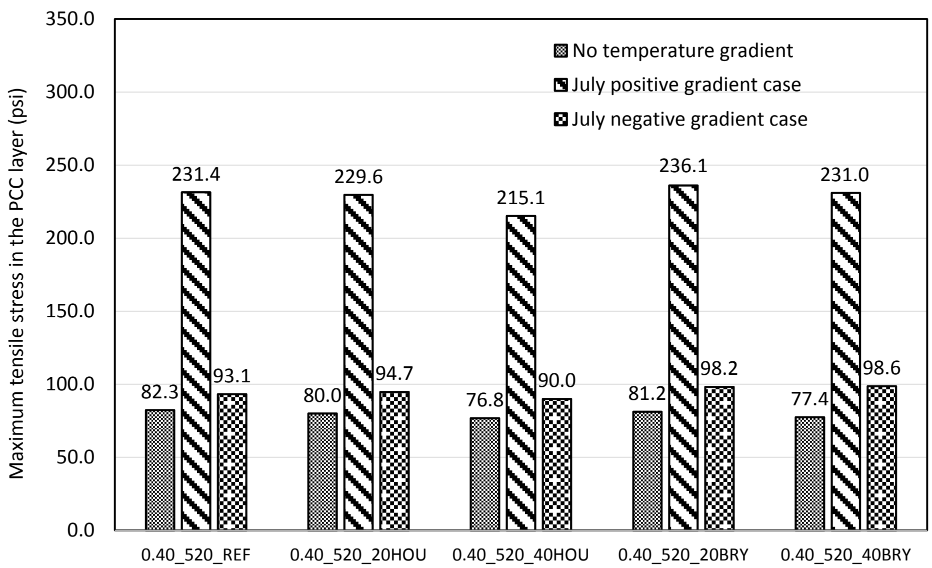


(a) Maximum tensile stress

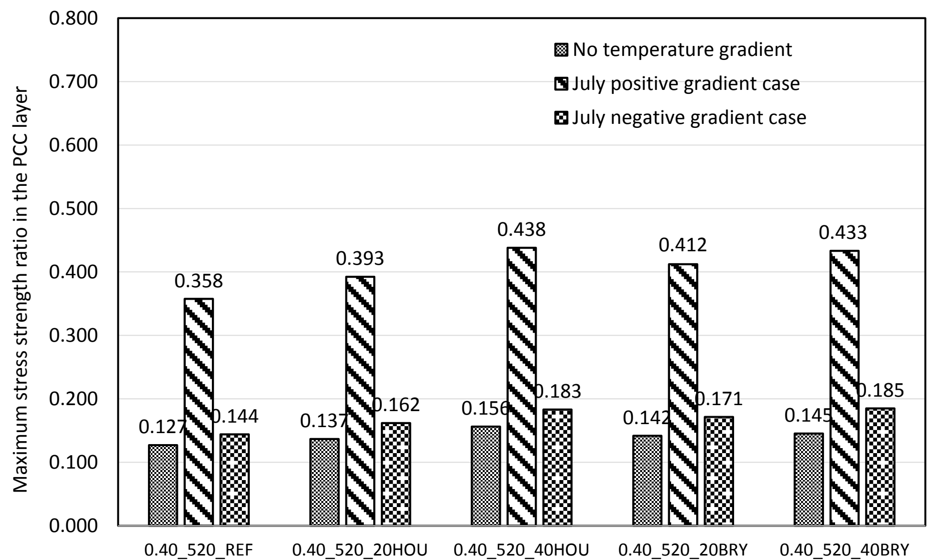


(b) Maximum stress strength ratio

Figure 83. Stress Analysis for the January Case.



(a) Maximum tensile stress



(b) Maximum stress strength ratio

Figure 84. Stress Analysis for the July Case.

The stress/strength is important to determine the cracking potential of the PCC slab. Figure 83 and Figure 84 show RAP-PCC all had slightly higher stress/strength ratio, which indicates the RAP-PCC may have slightly higher potential to cracking. A detailed distress evaluation will be conducted through the MEPDG simulation in the later section.

EFFECTS OF RAP-PCC ON CONCRETE PAVEMENT SLAB THICKNESS

From Chapter 2, it is confirmed that adding RAP into PCC led to reductions in mechanical properties. Therefore, the usage of RAP in PCC slab must be restricted by the material's strength requirement specified by Item 421. In this section, what are the real effects of the RAP-PCC material on pavement performances are evaluated.

PCC slab thickness is the major pavement design output. In Texas, the pavement slab thickness design shall follow the procedures specified in the TxDOT pavement design guide using TxDOT approved software or tools. For continuously reinforced concrete pavement (CRCP), the TxCRCP-ME, developed under TxDOT project 0-5832 (Ha et al. 2012), is the approved design tool. For concrete pavement contraction design (CPCD) or joint plain concrete pavement (JPCP), the use of the AASHTO 1993 design equation is allowed. Other than the TxCRCP-ME and the AASHTO 1993, the MEPDG is widely considered as a more advanced procedure, and several state DOTs have adopted it in the design specification. However, TxDOT has not approved the use of the MEPDG yet. Table 38 shows a comparison of the required material inputs for these three software. In this chapter, an analysis of full-depth pavements containing five different PCC mixtures was performed. The PCC mixes were RAP-PCCs with mix ID 0.40_520_20HOU, 0.40_520_40HOU, 0.40_520_20BRY, 0.40_520_40BRY, and the plain PCC (0.40_520_REF). Table 39 presents the material properties that were determined in in Chapter 2 used for the analysis.

Table 38. Comparison among TxCRCP, AASHTO 1993, and MEPDG.

Software	Pavement Type	Required Inputs for PCC Slab
TxCRCP-ME	CRCP	MOR
AASHTO 1993	CPCD (JPCP)	MOE, MOR
MEPDG	CRCP	Poisson's ratio, CoTE, unit weight, thermal conductivity, heat capacity, MOE, MOR, STS
	JPCP	Poisson's ratio, CoTE, unit weight, thermal conductivity, heat capacity, MOE, MOR

Table 39. Material Properties Inputs for the Pavement Designs.

Mix ID	Poisson's Ratio	CoTE (10-6/F)	Unit Weight (pcf)	Thermal Conductivity (BTU/hr-ft-deg F)	Heat Capacity (BTU/lb-deg F)	28-day MOE (ksi)	28-day MOR (psi)	28-day STS (psi)
0.40_520_REF	0.151	4.463	147.07	1.570	0.192	4779	647	636
0.40_520_20HOU	0.162	4.847	146.25	1.434	0.179	4198	585	646
0.40_520_40HOU	0.176	4.950	143.91	1.376	0.187	3554	491	549
0.40_520_20BRY	0.180	5.085	146.32	1.460	0.168	4164	573	606
0.40_520_40BRY	0.190	5.670	143.99	1.411	0.174	3490	533	573

Thermal conductivity and heat capacity were determined by hot disk measurement (Refer to Chapter 2)

TxCRCP-ME Results

The CRCP pavement design was completed using the TxCRCP-ME Excel® spreadsheet. The total design traffic was assumed as 20 million equivalent single axle loads (ESALs) in one direction, and the number of lanes in one direction was two. The pavement was assumed to be located in the Bryan District (Brazos County) with environmental conditions automatically determined by the spreadsheet. The subgrade classification was selected as CL based on Unified Soil Classification System (USCS) soil classification specification. A 6-in. cement treated base with modulus of 500 ksi was used in the design. A 30-year design period was used. In the design, all the inputs other than the concrete layer material properties remained constant among different cases. The concrete layer was assumed to be made with different RAP-PCC materials and a plain PCC, and their material inputs were selected in Table 39 (28-day MOR is the only input for TxCRCP-ME). The required pavement thickness was determined in which the predicted number of punchouts per mile was less than the design requirement (10 per mile). Table 40 shows the TxCRCP-ME design results for different RAP-PCC cases. The slab thickness requirement for the RAP-PCC increases very little (i.e., 0.5 in./5 percent) in comparison with the reference PCC at 20 percent RAP replacement level. However, at 40 percent RAP replacement level, the increase of thickness requirement is slightly higher (i.e., 1–2 in.,/10–20 percent) than that at 20 percent replacement level. Therefore, at a higher replacement level (> 20 percent), the CRCP containing RAP-PCC needs slightly higher slab thickness, which is related to the fact that the higher the RAP replacement the higher the reduction of MOR is. Based on the results, all the slab thickness remained within the range of the TxDOT specification for CRCP thickness (7–13 in.).

Table 40. CRCP Design Results.

Mix ID	Design Thickness (in.)	Punchouts at Design Thickness (Per mile)
0.40_520_REF	10	8.1
0.40_520_20HOU	10.5	9.3
0.40_520_40HOU	12	8.7
0.40_520_20BRY	10.5	9.7
0.40_520_40BRY	11	9.5

AASHTO 1993 Results

The CPCD was performed according to the AASHTO 1993 procedure with the assistance of an online CPCD design service (Pavement Interactive, 2017). The total design ESALs were 10 million. The reliability level of the design was 95 percent, and the combined standard error was set as 0.39. The initial serviceability index and the terminal serviceability index were set as 4.5 and 2.5, respectively. A drainage factor of 1.0 and a load transfer coefficient of 2.9 were assumed for all the design cases. A subgrade k value of 300 was used.

For different design cases, all the above mentioned inputs remained constant, while the PCC parameters varied according to the actual measured values for different RAP-PCC cases (i.e., 28-day MOE and 28-day MOR, Table 39). The designed slab thickness was rounded to the nearest 1/2 in. after the calculated thickness was obtained. Table 41 presents the CPCD results for different RAP-PCC cases. Similar with the CRCP cases, using a RAP-PCC in CPCD requires slab with slightly higher thickness; however, the differences in thickness between the pavements containing different RAP-PCC mixtures and the pavement containing plain PCC mixture were not significant. All the design thicknesses were within the range of the specification as well (6–12 in.).

Table 41. CPCD Design Results.

Mix ID	Calculated Thickness	Design Thickness
0.40_520_REF	10	10
0.40_520_20HOU	10.305	10.5
0.40_520_40HOU	11.205	11.5
0.40_520_20BRY	10.405	10.5
0.40_520_40BRY	10.705	11

MEPDG Results

The MEPDG, developed under the National Cooperative Highway Research Program 1-37A project, is considered a more advanced design tool to design pavements. However, the MEPDG has not been adopted by TxDOT yet, so the MEPDG results presented here might only be used for the comparison purpose. As shown in Table 38, the MEPDG simulation requires much more inputs than the TxCRCP-ME and the AASHTO 1993, so it can evaluate the change in pavement performance more extensively when the RAP-PCC is used in the pavement. In this MEPDG study, a typical pavement structure from Texas was selected (Figure 85). Since the primary interest in this analysis is to investigate how RAP-PCC can affect the slab thickness, only the materials properties for the RAP-PCC varied while the bases and subgrade properties remained unchanged during the simulations. Table 39 lists the PCC slab properties. In the design, College Station was selected as the climate station city to input the climate data. An average annual daily truck traffic (AADTT) of 30,000 was used for traffic input. All the other inputs adopted the default values.

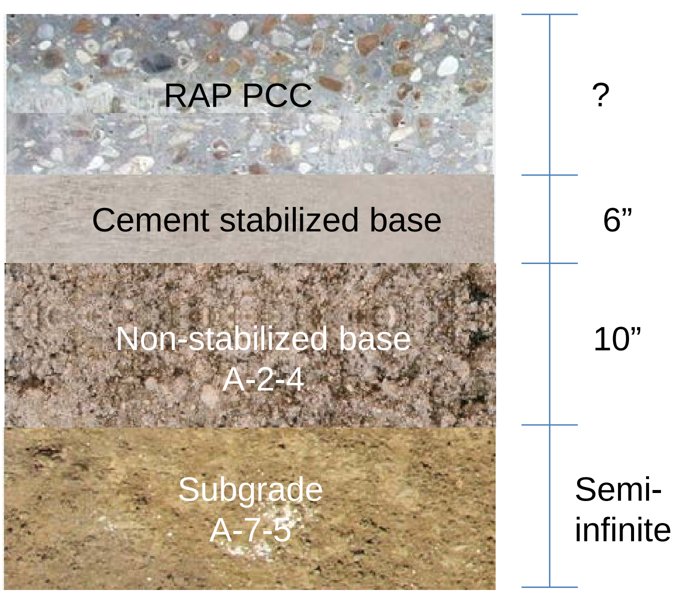


Figure 85. Pavement Structure Used in MEPDG Simulations.

In the MEPDG simulation, only the JPCP pavement design was considered. For the JPCP design, the pavement distress criterion are 172 in./mile for terminal international roughness index (IRI), 0.12 in. for mean joint faulting, and 15 percent for slab transverse cracking (all default values).

Table 42 lists the design results. Table 42 indicates that the use of RAP-PCC increased JPCP slab thickness. The primary failure distress turned out to be mean joint faulting. Using RAP-PCC had negative effects on the IRI, but it appeared to have no effect on the transverse cracking distress.

Table 42. MEPDG JPCP Design Results.

	Design Thickness (in.)	IRI (in./mile)	Mean Joint Faulting (in.)	Transverse Cracking (%)
0.40_520_REF	8	133.15	0.1	0.96
0.40_520_20HOU	9	140.86	0.11	0.96
0.40_520_40HOU	10	148.06	0.12	0.96
0.40_520_20BRY	10	137.1	0.1	0.96
0.40_520_40BRY	11	144.52	0.11	0.96

In order to understand the effect of each PCC material property on pavement distresses, a sensitivity analysis was conducted. The sensitivity analysis aimed at finding the material property of RAP-PCC that has the most significant negative effect on pavement performance, which might allow the researchers to come up with ideas and measures to mitigate the shortage of RAP-PCC. According to the sensitivity analysis, the following RAP-PCC properties were considered to have very significant effects on pavement performance:

- The increase in Poisson's ratio and CoTE by adding RAP in PCC caused negative effect on pavement IRI and joint faulting. The higher CoTE of RAP-PCC deteriorates JPCP pavement performance extremely significantly. The transverse cracking seems not be affected very much if a sufficient MOR was input.
- The reduced MOE of RAP-PCC material had a positive effect on pavement performance. The higher RAP replacement level, the softer the material, and as a result, the lower the predicted IRI and mean joint faulting values.

PAVEMENT LIFE CYCLE ASSESSMENT

According to the literature review in Chapter 1, although the current majority use of RAP is in HMA/WMA industry, most of the DOTs restrict the RAP usage in HMA since the addition of too much RAP is likely to cause a reduction in pavement cracking resistance. The limited use of RAP to make HMA/WMA has resulted in an excess of RAP in Texas and in some other states. According to a survey, it was reported that more than 91 percent contractors in United States had excess RAP (Hansen and Copeland 2015). The use of RAP in PCC can help mitigate the RAP stockpile problems. In this section, a study on life cycle assessment for RAP-PCC pavement application is presented.

In this life cycle assessment, an online software Economic Input-Output Life Cycle Assessment (EIO-LCA), developed by the Green Design Institute at Carnegie Mellon University, was used to estimate the resources cost, the energy requirement for RAP-PCC products, and the environmental emissions generated during the material production. The EIO-LCA adopted the famous economist Wassily Leontief's theory for which he received the Nobel Prize in Economics in 1973. The EIO-LCA provides free, fast, and easy life cycle assessment and has resulted in over 100 publications on the topic (Green Design Institute 2017).

Pavement Structure and Material Properties

Full-Depth Pavements

In the EIO-LCA, two full-depth pavements (plain PCC slab and RAP-PCC slab) with same slab thickness were considered. The thickness of the plain PCC slab was 10 in., which was obtained from the previous AASHTO 1993 pavement design procedures for CPCD. The thickness of the RAP-PCC slab was assumed to be 10 in. as well for comparison purposes. Although the previous sections showed the designed slab thickness for the RAP-PCC pavement may be slightly thicker, the validation of the design tools for predicting RAP-PCC construction material behavior has not been performed by any research yet. From the literature, the large-scale slab tests indicated the RAP-PCC slab had equivalent load capacity compared to the plain PCC (Brand 2012). Despite a reduction in strength, the toughness of RAP-PCC was comparable or even better than the plain PCC (Brand 2012). According to Bažant and Oh (1983), the fracture criteria may be more applicable to a large scale structure such as pavement than the strength criteria. Therefore, it is rational to assume a RAP-PCC full-depth pavement may have the same field performance with the plain PCC full-depth pavement with the same pavement thickness provided the surface properties (e.g., abrasion resistance/skid resistance) of RAP-PCC meet the requirements. So, a 10-in. slab was used for both the plain PCC pavement and the RAP-PCC pavement in the EIO-LCA. The pavements was assumed to be 3 mile long and 48 ft wide (two lanes in each direction and each lane was 12 ft), with slabs built with the mix design 0.40_520_REF for the plain PCC pavement and slabs built with the mix design 0.40_520_40BRY for the RAP-PCC pavement.

Two-Lift Pavement

According the TxDOT project 0-6749, two-lift concrete pavement would be a good option for applying recycled material like RAP-PCC. A two-lift concrete pavement contains a thinner top layer that uses high-quality concrete and aggregate, which aims at improving durability and skid resistance and reducing noise. A thicker bottom layer that has lower quality concrete and aggregate are used. The use of RAP-PCC in the bottom layer can reduce its negative effect on PCC pavement due to its reduced strength, increased CoTE, and reduced surface properties.

While two-lift pavement has been successfully applied in some of the Europeans countries, it has not been widely adopted in the United States. There are some field sections built in the United States, which are well documented in the final report from project 0-6749, but no detailed specifications on design procedure, lift thickness, and materials selection are published. A summary of information of existing two-lift construction is presented:

- Lift thickness: according to project 0-6749, most existing two-lift constructions used a 2–3 in. top layer. The minimum might be 1.6-in. top lift thickness from a practical standpoint because of the construction facility requirement. The thickness of the bottom lift was found to be around 7.8 in. in average.

- Material strength specification: There is no detailed specification on the material properties of the top lift and the bottom lift. Hu et al. (2014) in Table 43 summarized the statistics of the existing two-lift concrete pavement material properties.

Table 43. Statistics of the Existing Two-Lift Concrete Pavement Material Properties.

	Top Lift		Bottom Lift	
	Average	Standard deviation	Average	Standard deviation
Thickness	2.6"	0.9"	7.8"	1.5"
Cement content	579 lb/cy	108 lb/cy	512 lb/cy	60 lb/cy
w/c	0.42	0.03	0.44	0.02
Slump	1.6"	0.9"	1.38"	0.94"
Air	0.06	0.018	0.062	0.01
fc	4600 psi	922 psi	4100 psi	548 psi
MOR*	640 psi	NA	371 psi	NA
Aggregate type	High quality aggregate (granite, rhyolite, basalt, etc.)		Local aggregates (limestone sand, river gravel, RCA, RAP, etc.)	

***** One datum

Because there is no published specification for the two-lift pavement in Texas, a two-lift concrete pavement whose thickness and material properties are within the normal range of existing field cases (Table 43) was used in the EIO-LCA. In order to be compared with the full-depth pavements, the two-lift pavement was assumed to have the same total slab thickness with the above-mentioned full-depth pavements (10 in.); the top lift was assumed to be 2-in. thick and the bottom lift was 8-in. thick, which were close to the averaged values reported in Table 44. According to 0-6479, there was only one MOR value reported from the existing cases, which was 640 psi for the top lift and 371 psi for the bottom lift. After a careful examination of the experimental data in Chapter 2, it is rational to use the 0.40_520_REF for the top lift and the 0.40_520_100BRY for the bottom lift of the two-lift pavement in the EIO-LCA because the 56-day MOR for the 0.40_520_REF was 663 psi (higher than 640 psi) and the 56-day MOR for the 0.45_656_100HOU was 472 psi (much higher than 371 psi). Although there are no MOR data available for the 0.40_520_100BRY, considering the BRY is a RAP with better qualities compared to the HOU, the 0.40_520_100BRY shall have a MOR that is no less than 472 psi.

EIO-LCA Procedure and Results

According the justification explained in the previous sections, Figure 86 presents the pavement structures used in the EIO-LCA for the comparison purpose. Table 44 presents the related parameters that were required to perform the analysis in this study.

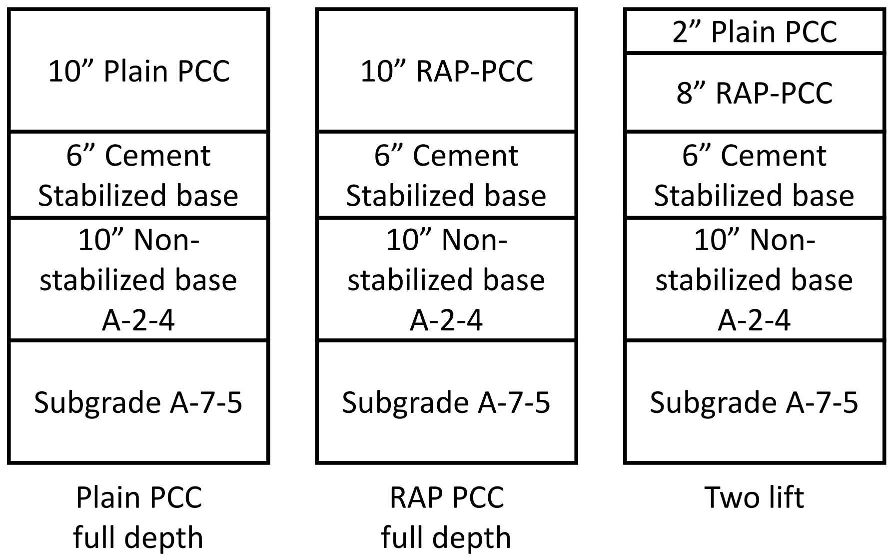


Figure 86. Pavement Structures Used in EIO-LCA.

Table 44. Pavement Information Used in the EIO-LCA Study.

EIO-LCA Case	Mix ID	Pavement Length	Pavement Width	Pavement Slab Thickness	Total Volume of Concrete
Plain PCC full-depth	0.40_520_REF	3 miles	48'	10"	23467 cy
RAP-PCC full-depth	0.40_520_40BRY	3 miles	48'	10"	23467 cy
Two-lift	Top lift: 0.40_520_REF Bottom lift: 0.40_520_100BRY	3 miles	48'	Top lift: 2" Bottom lift: 8"	Top lift: 4693 cy Bottom lift: 18773 cy

The material cost for each ingredient of concrete in Bryan, Texas, is obtained in the 2017 RS Means database (RS Means 2017).

Table 45. Material Unit Cost for PCC Ingredients.

Ingredient	Description	Unit Cost in 2017 Value
Cement	Cement, portland, type I/II, trucked in bulk, includes material only	162 dollars/ton
Fly ash	Concrete admixture, recycled coal fly ash	63.50 dollars/ton
Virgin coarse aggregate	Coarse aggregate, stone, ¾" to 1-1/2", prices per ton, includes material only	21.50 dollars/ton
RAP	RAP in the excess stockpile, considered as wastes that need to be consumed	0 dollars/ton
Virgin fine aggregate	Fine aggregate, washed concrete sand, loaded at the pit, includes material only	23.50 dollars/ton
Water reducer	Mid-range water reducer, includes material only	0.018 dollars/gallon
Air entraining agent	Concrete admixture, air entraining agent, 0.7 to 1.5 oz per bag, 55 gallon drum, includes material only	15.7 dollars/gallon
Water*	Commercial domestic	0.60 dollars/ton

*Obtained from College Station Utilities website (College Station 2017).

Based on the total concrete material needed (Table 44), the mix design information (Table 13) and the material cost (Table 45), the total weight and cost of each material was calculated. Table 46 presents the results. The cost of RAP was 0 because it is assumed that the RAP material is from excess stockpile and is considered as waste in this assessment. Actually, using RAP to make PCC can help reduce the size of excess RAP stockpiles, save cost on extra expense on stockpile management, and reduce the negative effects of RAP stockpile on environment and residents; so using the RAP in PCC should yield a negative cost. However, due to the difficulty to quantify these positive effects in terms of currency, zero cost of RAP is assumed in the EIO-LCA. Future research is highly warranted to further improve this analysis by including the benefits of using RAP in the calculation.

Table 46. Cost of Each Material.

Material	Unit Price	Amount Needed			Material Cost		
		Plain PCC pavement	RAP-PCC pavement	Two-lift pavement	Plain PCC pavement (k dollars)	RAP-PCC pavement (k dollars)	Two-lift pavement (k dollars)
Cement	162 dollars/ton	4881 ton	4881 ton	4881 ton	790.73	790.73	790.73
Fly ash	63.50 dollars/ton	1220 ton	1220 ton	1220 ton	77.49	77.49	77.49
Virgin coarse aggregate	21.50 dollars/ton	20,921 ton	12,085 ton	4148	449.79	259.84	89.96
RAP	0	0	8061 ton	15,263 ton	0	0	0
Virgin fine aggregate	23.50 dollars/ton	15206 ton	15,488 ton	15,741 ton	357.35	363.97	369.92
Water reducer	0.018 dollars/gallon	1907 gal	1907 gal	1907 gal	0.03	0.03	0.03
Air entraining agent	15.7 dollars/gallon	287 gal	287 gal	287 gal	4.50	4.50	4.50
Water	0.60 dollars/gallon	2441 ton	2441 ton	2441 ton	1.45	1.45	1.45

A U.S. 2002 purchaser model custom model in the EIO-LCA was then used to calculate the resources, energy requirement, and the environmental emissions during the production of these construction materials. The current life cycle assessment only aims at evaluating the cost and environmental impacts induced by purchasing construction materials, with no analysis for the pavement construction and maintenance activity included. In the assessment, seven different sectors were added to the model. Table 47 summarizes the sector names and the amount of economic activity.

Table 47. Sectors Names and Amount of Economic Activity.

Material	Sector Group	Detailed Sector	Amount of Activity (dollars)		
			Plain PCC pavement	RAP-PCC pavement	Two-lift PCC pavement
Cement	Plastic, rubber, and nonmetallic mineral products	Cement manufacturing	790,734	790,734	790,734
Fly ash	Plastic, rubber, and nonmetallic mineral products	Cement manufacturing	77,487	77,487	77,487
Virgin coarse aggregate	Mining and utilities	Stone mining and quarrying	449,792	259,835	89,958
RAP	Not included in the EIO-LCA	Not included in the EIO-LCA	0	0	0
Virgin fine aggregate	Mining and utilities	Sand, gravel, clay, and refractory mining	357,351	363,969	369,924
Water reducer	Petroleum and basic chemical	Other basic organic chemical manufacturing	35	35	35
Air entraining agent	Petroleum and basic chemical	Other basic organic chemical manufacturing	4499	4499	4499
Water	Mining and utilities	Water, sewage and other systems	1454	1454	1454

After inputting the amount of economic activity in different sectors in the model, the life cycle assessment was performed in an easy and fast manner by the online software. The outputs of the analysis included economic activity, conventional air pollutants, energy, greenhouse gasses, land use, toxic releases, transportation, water withdrawals, and Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts impact assessment. Selective results are presented and discussed as below.

Economic Activity

The economic activity presents the transaction needed to yield the final products. Figure 87 compares the economic activity for the three different pavement types. Figure 87 shows that the RAP-PCC full-depth pavement yielded less economic activity than the plain PCC pavement, while the two-lift pavement yielded the least. This means the material production of the two-lift pavement is the cheapest. Figure 88 presents the percentage reduction of RAP-PCC pavements (both full-depth and two-lift). The percentage reduction is defined as the percentage difference between the RAP-PCC pavement (either full-depth or two-lift) and the plain PCC pavement normalized by the plain PCC pavement. From Figure 88, it is concluded that the reductions in the total economic activity of the RAP-PCC full-depth pavement and the two-lift pavement are 10.48 percent and 20.43 percent, respectively. These reductions are due to the less consumption of virgin coarse aggregate in RAP-PCC pavements.

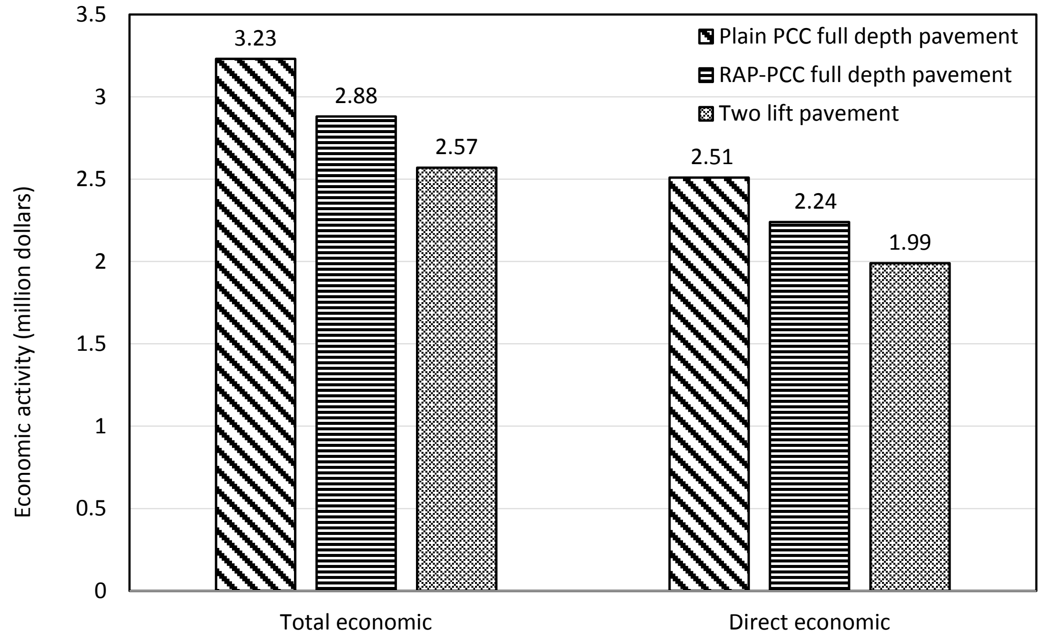


Figure 87. Comparison of Economic Activity.

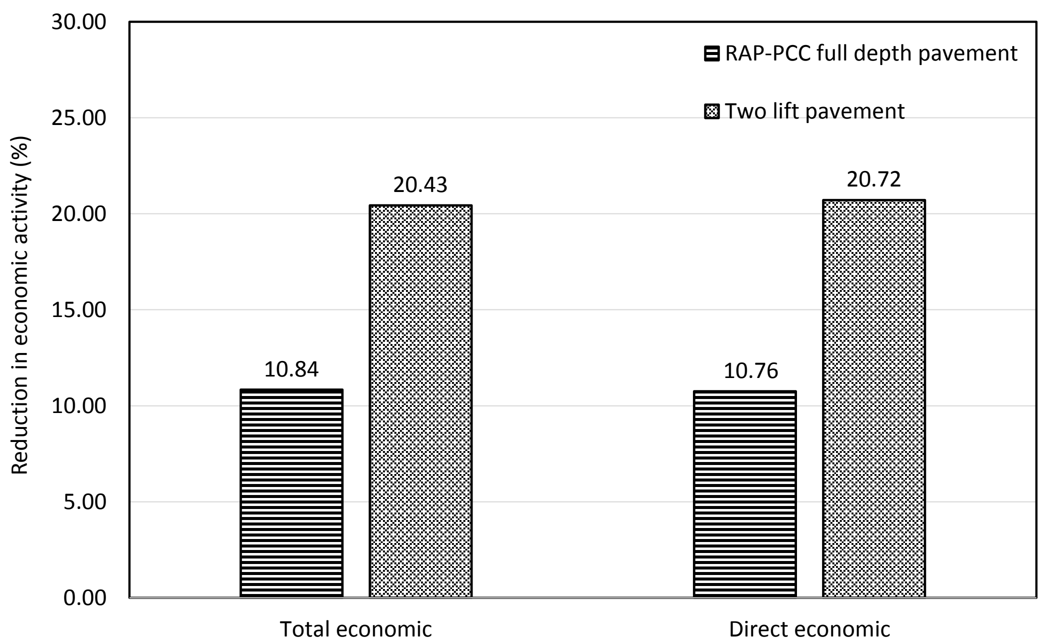


Figure 88. Reduction in Economic Activity.

Conventional Air Pollutants

The conventional air pollutants including CO, NH3, NOx, PM10, PM2.5, SO2, and VOC were predicted using the software/model, and Figure 89 and Figure 90 show the results. Figure 89 shows that the production of construction materials would produce significant amount of air pollutants, and mostly are NOx, CO, SO2, and PM10. By using RAP in PCC, the amounts of air pollutants generated could be less for all the pollutant categories. Figure 90 indicates that the use of recycled coarse aggregate helped reduce the PM10 and PM2.5 very significantly.

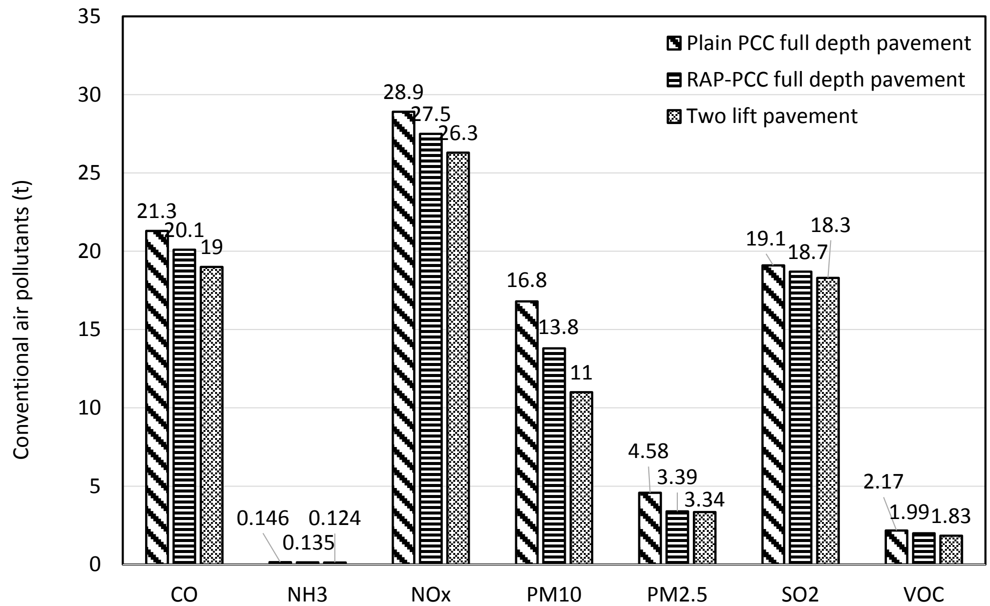


Figure 89. Comparison of Conventional Air Pollutants.

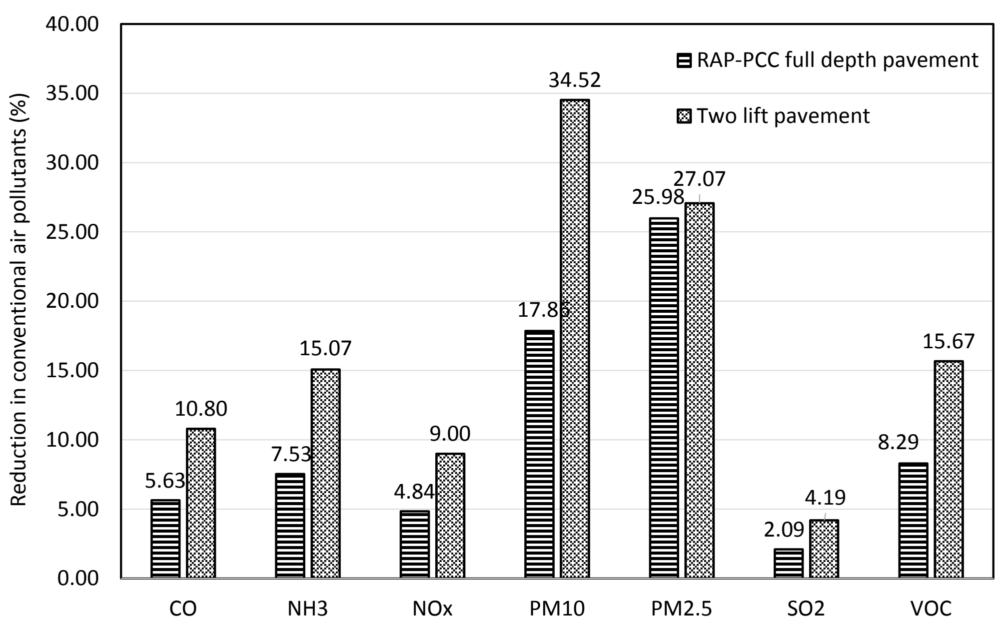


Figure 90. Reduction in Conventional Air Pollutants.

Energy

The energy required during the activities was calculated and presented in Figure 91 and Figure 92. The energy included coal, natural gas, petroleum, biomass/waste, and non-fossil fuels. According to Figure 92, the total energy saved by less raw material consumption (i.e., virgin coarse aggregate) in producing the RAP-PCC full-depth pavement and the two-lift pavement reached to 4.88 percent and 9.17 percent. Among the energy category, the petroleum energy could be saved in the most significant amount.

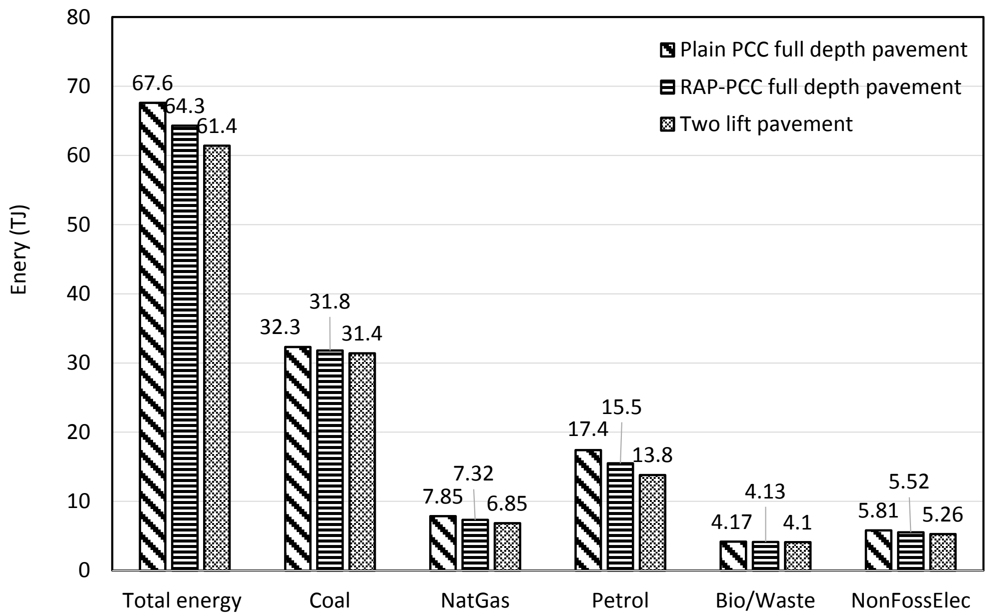


Figure 91. Comparison of Energy.

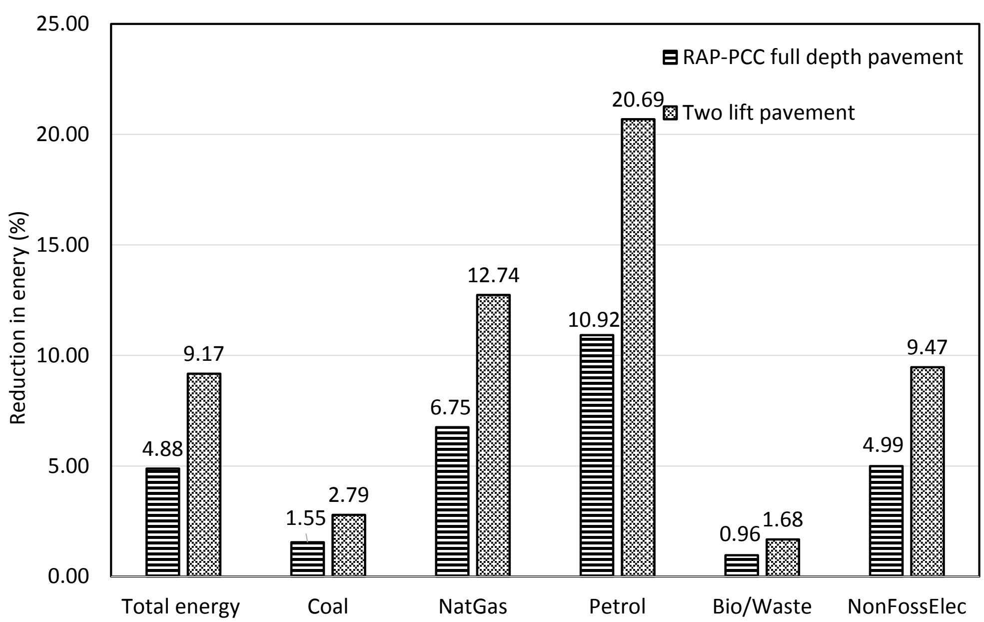


Figure 92. Reduction in Energy.

Greenhouse Gases

The amount of greenhouse gases generated during the activities was calculated in Figure 93 and Figure 94. The results are measured in terms of global warming potential, which presents how much greenhouse gases trap in the atmosphere (Shine et al. 2005). The unit of global warming potential is metric tons of carbon dioxide equivalent emissions (t CO2e) (Mao 2012). Figure 93 shows that most of greenhouse gases were generated from fossil and process. By applying RAP in concrete, 2.43 percent and 4.75 percent of greenhouse gases can be reduced for the full-depth and the two-lift pavement, respectively.

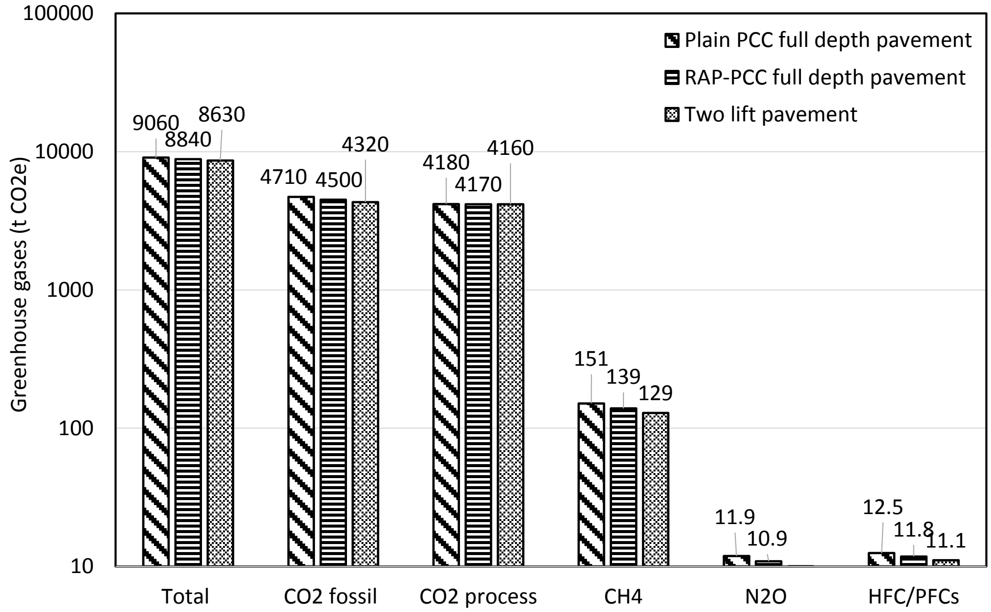


Figure 93. Comparison of Greenhouse Gases.

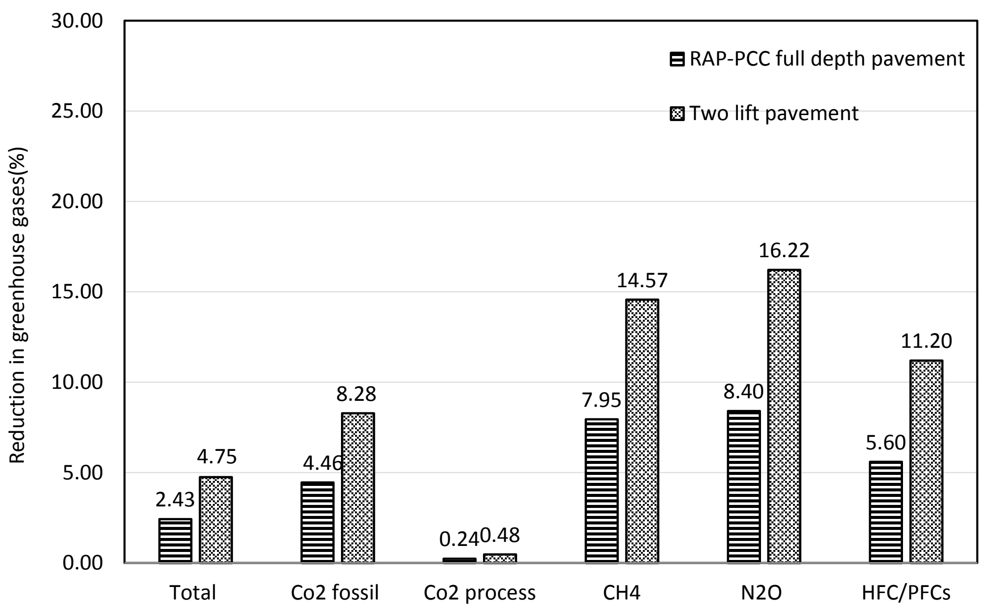


Figure 94. Reduction in Greenhouse Gases.

Land Use

According to Figure 95, the production of RAP-PCC pavements yielded less land use. The percent reductions in land use are 11.11 percent and 20.37 percent for the RAP-PCC full-depth pavement and the two-lift pavement, respectively.

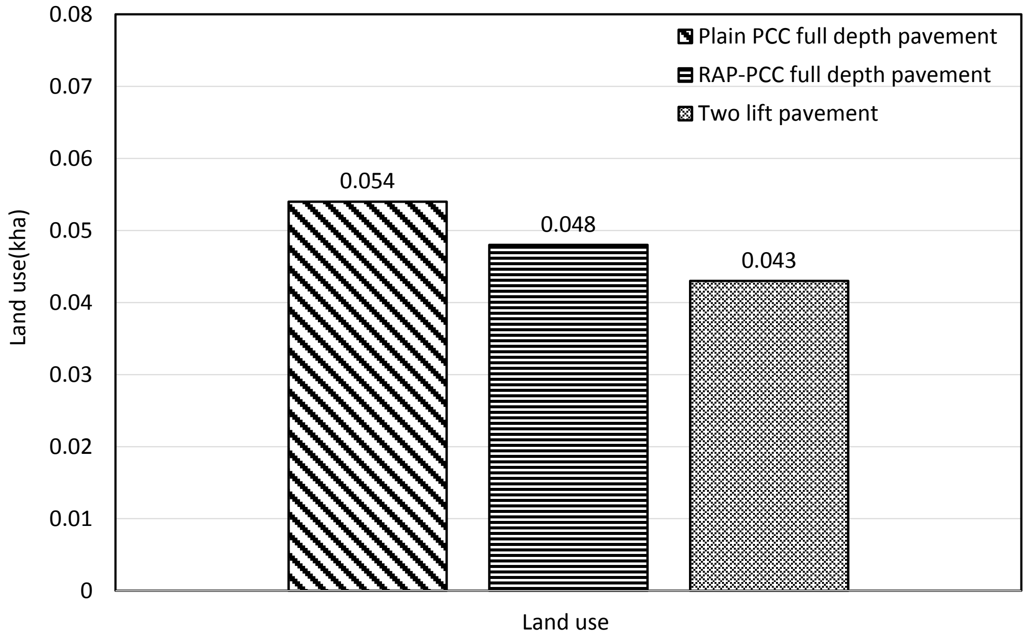


Figure 95. Comparison of Land Use.

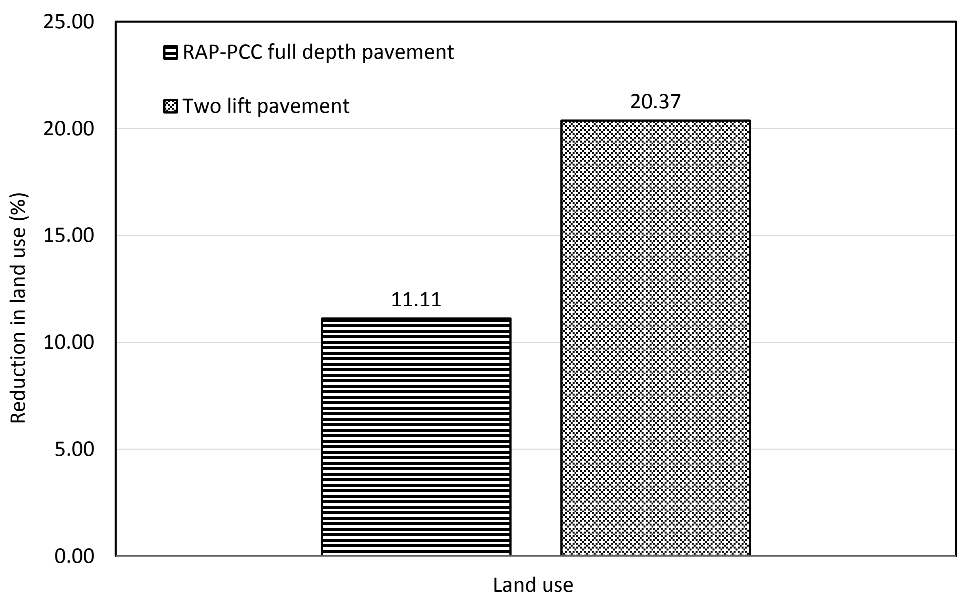


Figure 96. Reduction in Land Use.

Toxic Releases

During the production of PCC pavements, toxic materials including fugitive air release, stack, total air release, surface water release, underground water releases, land release, offsite, publicly owned treated works (POTW) metal, and POTW nonmetal were produced. Figure 97 shows that the process of producing pavement materials released mostly stack, air, and land toxics. By consuming less virgin coarse aggregate, less toxics were released to the environment. Figure 98 suggests that the offsite, underground water, and fugitive were among the highest reduction categories.

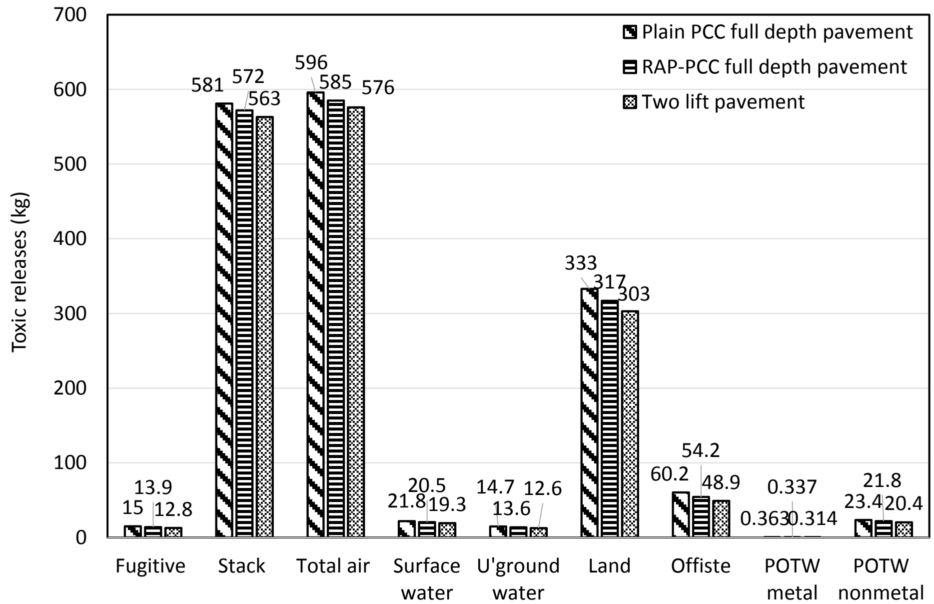


Figure 97. Comparison of Toxic Release.

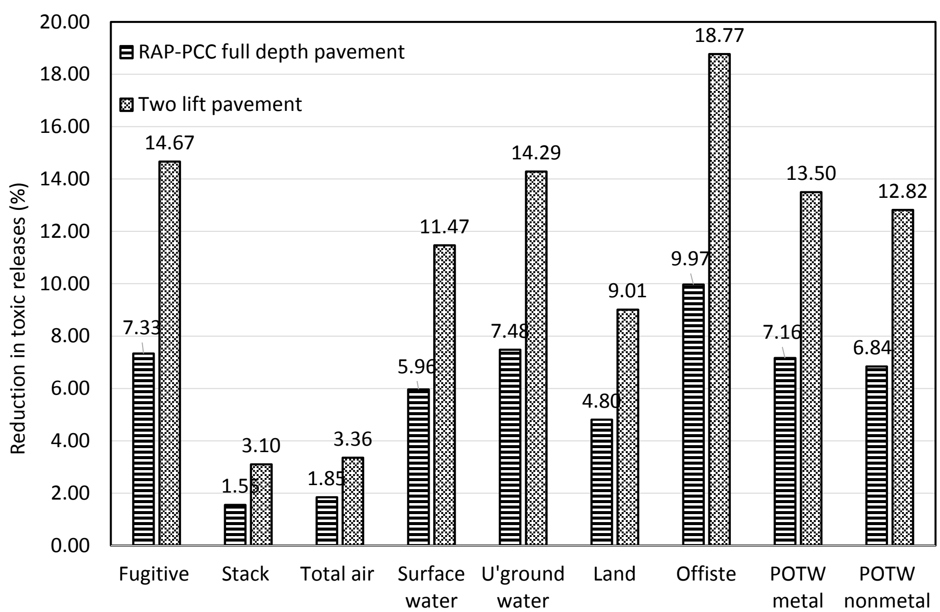


Figure 98. Reduction in Toxic Releases.

Water Withdrawals

Figure 99 compares the water withdrawals for the construction of plain PCC pavement and for the construction of pavements containing RAP-PCC materials. The construction of RAP-PCC pavement consumed less amount of water, which is largely due to the significantly less amount of water withdrawn in stone mining and quarrying process. By using RAP, the reduction in the water withdrawal could be 14.17 percent and 26.90 percent depending on the pavement types (Figure 100).

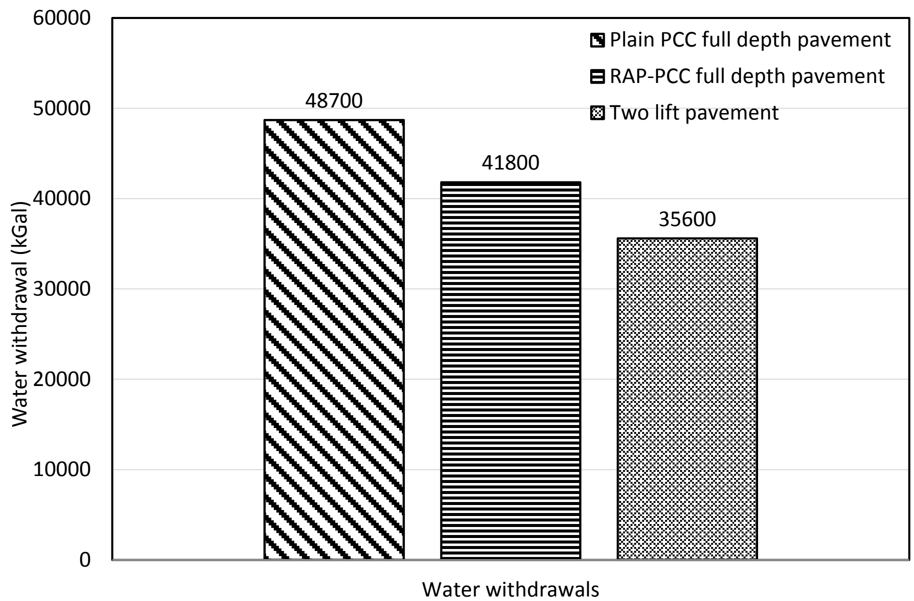


Figure 99. Comparison of Water Withdrawals.

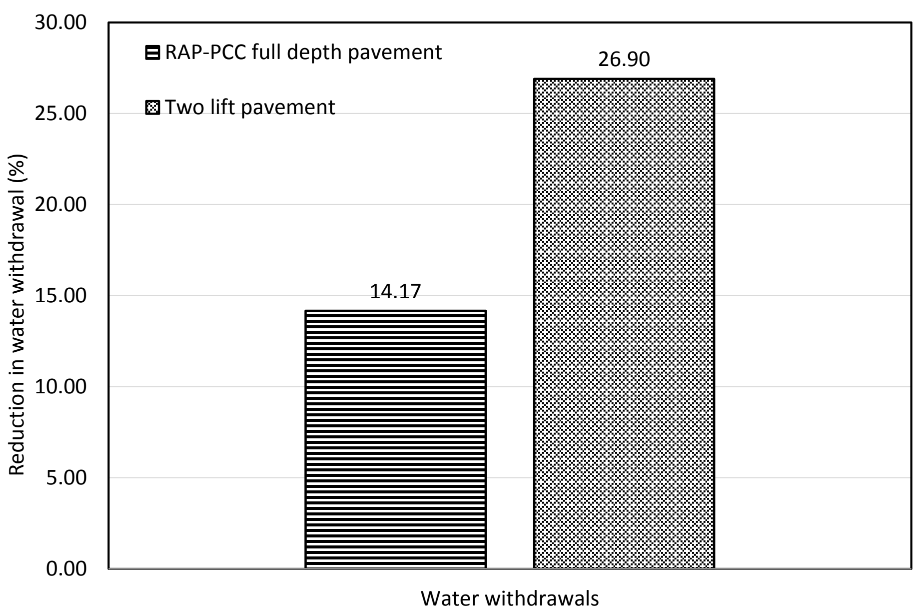


Figure 100. Reduction in Water Withdrawal.

RAP Stockpile Reduction by Using RAP in PCC

The increasing production of RAP increases the need for material stockpiling. In general, the following list of expenses and environmental impacts for aggregate material stockpiling is considered (Lender 2016):

- Fuel costs for truck and loaders: significant amounts of fuel for the vehicles during the initial construction and maintenance of the stockpiles.
- Original equipment investment: as with most plant systems, stockpiling has the automation option to reduce the chance of accidents. This contributes to large amounts of hardware and software investments.
- Maintenance cost for equipment: investment needs to be made on stockpiles maintenance such as hiring personnel, safety training, space arrangement, clean up, etc.
- Mine Safety and Health Administration (MSHA) fines for safety violation: MSHA established strict policies to protect the personnel and the public. Any violation will lead to serious punishments.
- Space costs: RAP stockpiles occupy large amount of space. According to the MSHA, a clearance of at least 10 ft from the apex of the stockpile and live power lines is required. How to and where to stockpile the RAPs will become a problem if large amounts of RAP are produced.
- Dust production: Stockpiling produces lots of dust, which threatens people's health.

According to Table 46, to construct a 3-mile, four lanes RAP-PCC full-depth pavement and a 3-mile, four lanes two-lift pavement with structures shown in Figure 86, the consumption of coarse RAP can be 8061 and 15263 tons, respectively. Assuming the capacity of a conical stockpile (37° repose angle) for a 50 ft conveyor length is 500 ton (Lender 2016), around 16 and 31 RAP stockpiles would be consumed to construct a full-depth pavement and a two-lift pavement, respectively. This will lead to greater savings in terms of both economics and environment. The quantification of these positive impacts warrants further research.

CONCLUSIONS

The RAP-PCC pavement performance was evaluated through slab stress analysis and pavement distress analysis by various tools. The life cycle assessment of three different pavements was performed through the EIO-LCA model. The following conclusions are made from the findings in this study:

- Using RAP concrete as PCC layer in pavement yielded reduced maximum tensile stress when no temperature or positive temperature gradients (profile) were assigned. However, the stress/strength was slightly higher due to the low tensile strength of the RAP-PCC.
- At higher replacement level (>20 percent), the pavement containing RAP-PCC needs slightly higher slab thickness. A slight increase in thickness is largely caused by the increase in CoTE and Poisson's ratio and the reduction in MOR when RAP is added into concrete.
- The decreased MOE of RAP-PCC had positive effect on pavement performance (i.e., reduced IRI and mean joint faulting).

- Compared with the material production for plain PCC pavement, the production of materials for constructing RAP-PCC pavements (either full-depth or two-lift) yielded more economical option and consumed less amounts of energy. It released less amounts of air pollutants, greenhouse gases, and toxic materials. It also led to less amounts of land use and water withdrawals.
- The idea of using RAP-PCC as bottom lift in a two-lift PCC pavement can maximize the RAP usage without compromising the pavement performance or compromise within the permissible limits. The cost and environmental benefits were obvious among all three pavement types.
- Other than the benefits from material production process, the use of RAP in PCC can reduce the size of the RAP stockpile significantly, which leads to cost savings and protecting environment and public safety.

CHAPTER 5. GUIDELINES AND IMPLEMENTATION RECOMMENDATIONS

Based on findings from the literature review (Chapter 1), laboratory tests (Chapter 2), and pavement performance simulations (Chapter 4), researchers concluded that the use of RAP in PCC is largely feasible for the pavement application. Despite the fact that RAP-PCC yielded reduced mechanical properties (especially different strengths), a proper utilization of optimized aggregate gradation benefits from using RAP and the use of RAP-PCC as a bottom lift in a two-lift pavement construction can compensate the strength reduction and allow more RAP in the mixture. An even higher amount of aggregates (both coarse and fine) can be replaced to make full use of RAP to make low strength PCC for the other applications such as curbs, gutters, sidewalks, etc. Considering the factors related to strength, materials, construction, and performance, researchers developed the following guidelines.

GUIDELINES

Material Selections and Mix Design

The properties of RAP vary significantly. To make a RAP-PCC with less strength reduction and adequate durability, a good quality RAP material is needed. The RAP materials characterized by lower asphalt binder content (for a coarse RAP, <5.0 percent; for an intermediate RAP, <7.0 percent) and lower amount of agglomerated particles are generally considered as good quality RAPs. Asphalt cohesive failure was found to be the main failure mechanism in RAP-PCC (Chapter 3). In the cohesive failure, cracks easily pass through the asphalt layer in RAP-PCC. Therefore, the higher the binder content the higher the chances of occurrence of cohesive failure are. The use of coarse RAP alone satisfies low binder content requirements in general.

Fine RAP (particles passing No. 8 sieve) is not suitable to make RAP-PCC for the pavement application because 1) it contains higher binder content than the coarse RAP and would induce a more significant reduction in workability and strength; and 2) the high amount of asphalt binder in fine RAP can be re-used in the HMA/WMA industry more economically. Fine RAP can be used along with coarse RAP to make PCC for non-pavement low strength applications in order to maximize RAP usage. The use of fine RAP is very important if there is an excess amount of fine RAP or the fractionation of RAP is an issue.

RAP materials generally contain some amount (amount varies) of intermediate size particles (passing 3/8 sieve and remained on #8 sieve) and replacing virgin aggregate with RAP containing adequate amounts of intermediate size particles actually introduces dense aggregate gradation in RAP-PCC mixtures. Therefore, RAP source with adequate amounts of intermediate size (>50 percent) particles is highly preferable to achieve a RAP-PCC mix with dense graded benefits. Coarse RAP materials generally contain intermediate size aggregate particles by default as dense aggregate gradation is commonly used to make HMA mixtures for pavement applications. RAP-PCC mixes with dense aggregate gradation help enhance workability and strength and compensate higher strength reduction normally observed in absences of dense aggregate gradation. Chapter 2 presented coarse RAP materials with ideal gradation range requirements to make RAP-PCC mixes for pavement applications.

Meet TxDOT Class P Strength Requirement Criteria for Full-Depth Pavement Application

The asphalt in the RAP is considered the major cause of the strength reduction in a RAP-PCC system. Therefore, the asphalt content (i.e., the RAP replacement level) in the mixture needs to be strictly controlled to ensure that the DOT strength requirements are met. Based on the analysis and discussion in Chapter 2, the 28-day flexural strength can be selected as strength criteria because: 1) The flexural strength is considered to be an important and relevant parameter related to concrete pavement performance because concrete is weak in tension and its tensile strength should be strictly controlled under traffic and environmental loading. The TxDOT pavement design guide approves use of TxCRCP-ME and AASHTO 1993 to design CRCP and CPCD (JPCP) slab thickness, respectively; both of them require 28-day flexural strength as material input, while the compressive strength is not needed. And 2)The RAP-PCC had slower flexural strength growth over time than that required by the specification, so meeting the 28-day flexural strength requirement may be considered a conservative way to estimate the replacement level.

The following procedures are recommended for designing a RAP-PCC that meets TxDOT's Class P strength specification:

1. Select a good quality of coarse RAP material and test asphalt binder content for the selected RAP according to ASTM D 6307. A RAP material with greater amounts of intermediate size particles (to achieve dense graded gradation) and lower ranges of asphalt binder content (to ensure higher RAP replacement level) is desirable. Chapter 2 presents coarse RAP materials with ideal gradation range requirements to make RAP-PCC mixes for pavement applications. Researchers recommend that contractors generate RAP stockpile materials satisfying the gradation requirements.
2. Design RAP-PCC mixtures by replacing 20 percent coarse RAP and 40 percent coarse RAP, respectively. If possible, adding one more point (30 percent) is highly recommended.
3. Cast and cure RAP-PCC samples as well as the reference sample designed in step 2; test samples' mechanical properties at 28 days. Researchers recommend testing 28-day flexural strength. If the flexural strength test is not applicable, testing compressive strength is allowed.
4. Construct a regression relationship between the 28-day flexural strength (or compressive strength if it was tested in step 3) and the GABVF. The equation to determine GABVF can be found in Chapter 2.
5. Determine the optimum GABVF in accordance with the target flexural strength. For TxDOT Class P specification, the 28-day flexural strength requirement is 570 psi. If 28-day compressive strength is tested in step 3, the target compressive strength requirement can be set as 3906 psi (determined by using the modified ACI correlation equation developed in this study; refer to Chapter 2). Back-calculate the optimum RAP replacement level using mix design information.

Meet TxDOT Different Strength Requirement Criteria for Low-Strength Applications

Although the production of RAP-PCC for full-depth pavement application is restricted to coarse RAP replacement alone at this point, the use of fine RAP (alone or combined with coarse RAP) for low-strength PCC applications is allowable. This use of fine RAP in PCC can maximize RAP usage if excess fine RAP is available or the RAP fractionation becomes an issue. The guideline for making RAP-PCC mixes that meet lower strength requirements (class A, B, C, E, S, and SS) are presented below.

If time and expense permit, a robust method to determine the optimum RAP replacement level is always encouraged. This approach, performed through a case by case experimental study, can ensure better accuracy in determining RAP replacement. The following procedures are recommended:

1. Select a RAP material and test asphalt binder content for the selected RAP according to ASTM D 6307.
2. Design RAP-PCC mixtures by introducing RAP at various replacement levels covering the entire range (e.g., 0 percent, 20 percent, 40 percent, 70 percent, and 100 percent). If both of the coarse and fine RAPs are used, replace virgin coarse aggregate with coarse RAP and replacing virgin fine aggregate with fine RAP at designed replacement levels, respectively. If only coarse RAP or fine RAP is used, replacing the corresponding virgin aggregate at designed replacement levels.
3. Cast and cure RAP-PCC samples as well as the reference sample designed in step 2; test samples' 56-day compressive strength.
4. Construct a regression relationship between the 56-day compressive strength and the GABVF. The equation to determine GABVF can be found in Chapter 2.
5. Select the best regression equation for describing the compressive strength and binder fraction relationship. If the maximum GABVF for the tested RAP-PCC is smaller than 3.5, a linear relationship might be valid. Otherwise, a logarithmic relationship might be more suitable.
6. Determine the optimum GABVF in accordance with the target 56-day compressive strength specified by different concrete class in Item 421. (i.e., 2000 psi for Class B, 3000 psi for Class A and E, 3600 psi for Class C and Class SS, and 4000 psi for Class S). Back-calculate the optimum RAP replacement level using mix design information.

The following procedures provide an approach for designing RAP-PCC mixtures that meet TxDOT's different strength specifications in a less robust way, provided the time and expense are limited or the strength requirement is less crucial:

1. Select a RAP material and test asphalt binder content for the selected RAP according to ASTM D 6307.
2. Determine the mix design for the reference PCC and test its 56-day compressive strength.
3. Select the target 56-day compressive strength requirement based on the different class requirement; calculate the allowable percent reduction between the reference PCC compressive strength and the target one.
4. Using the generalized correlation equation proposed in Chapter 2: $\%red = 26.455 \times \ln(\theta) + 6.2264$ to estimate the allowable GABVF. Back-calculate the optimum RAP replacement level using mix design information.

Due to fact that the RAP properties can vary with time and sample selection, it is highly recommended to cast and test RAP-PCC with designed RAP replacement according to the procedures that are described above to verify the mixture has the specified strength.

Selection of RAP-PCC Pavement Type

A significant amount of further work is needed in order to develop procedures for better selection of a RAP-PCC structure that satisfies the requirements of mechanical performance and sustainability (i.e., ensuring the positive effects on economics, environment, and human life). Based on the findings to date from this study, the following recommendations are made.

- If the designed RAP-PCC can satisfy the requirements of adequate surface characteristics and mechanical properties, a full-depth pavement containing a RAP-PCC slab might be feasible. To satisfy the requirements of adequate surface characteristics, a RAP-PCC mixture needs to meet the requirements of abrasion resistance/skid resistance, noise reduction, and ride quality. A detailed study on determining these properties followed by performance prediction matching with field conditions is an important area of further research. Suitable mechanical properties (e.g., MOR, CoTE) can be controlled by replacing adequate amounts of RAP in PCC with the design approaches described in the previous section. It is still recommended to use TxDOT approved design tools to determine the RAP-PCC pavement thickness. However, it is important to validate through lab and field tests that a RAP-PCC slab of the same thickness can show equivalent performance as a plain PCC slab. Although an increase in pavement thickness will lead to higher cost, which might cancel out the materials savings in using existing recycled material, the positive impacts on environment and public safety due to consuming fewer natural stones, and the removal of RAP stockpiles may still make the project beneficial.

- If the designed RAP-PCC has undesirable surface characteristics for serving as a top layer, a two-lift pavement might be a good option. Since there is no specification for the two-lift pavement in terms of material properties, mix design, and structure design, two-lift pavement construction is considered as an option in the United States and requires future work before it can be implemented in the field. From the case study of exiting two-lift pavements, a 2–3 in. top layer and a 6–10 in. bottom layer are within the normal ranges. The RAP-PCC shall be used to construct the bottom layer; the procedure to design the RAP-PCC material for a bottom lift can be established once the material specification for two-lift pavement comes out. It is anticipated to use a RAP-PCC material with low cementitious content and a high RAP replacement level for the bottom lift, which can be a more economical and environmentally friendly option for future pavement construction.

IMPLEMENTATION AND FUTURE WORK

Based on the above-mentioned guidelines, an implementation plan with proposed further research work is presented below in order to further evaluate the RAP-PCC properties and carry out the guidelines in field applications:

- Testing additional RAP materials covering a wide range of materials representing different geographic locations:
    - Generate RAP satisfying the gradation requirements proposed in Chapter 2; the current study actually used the RAP materials from the existing stockpiles in HMA

plants to make PCC. It is important to work with the industry to develop effective procedures to make RAP materials with the required gradation from the reclaimed asphalt materials to make PCC.
    - Develop better RAP characterization techniques to help select RAP and to better predict RAP-PCC properties. Significant efforts need to be made to investigate the effect of RAP quality and mix design strategy on RAP-PCC properties. Specifically, research needs to be done to correlate or interpret the factors that affect the rate of deterioration k, which is a parameter representing how significant the negative effect of RAP on PCC properties (refer to Chapter 2). As an example, other than the binder content and RAP gradation, it is highly recommended to introduce the degree of RAP agglomeration. The degree of RAP agglomeration can be quantified using petrographic methods.
- Additional mechanical tests:
    - Creep test: The addition of the RAP is anticipated to cause more creep for PCC because of the viscoelastic nature of asphalt material. This assertion needs to be verified and the effect of increased creep caused by the RAP on PCC pavement performance should be investigated through finite element method simulation.
    - Fracture toughness and fatigue tests: The criteria to judge the feasibility of the use of the RAP in PCC in this study was the material strength criteria. According to Bažant and Oh (1983), "when the structure is relatively large, the crack band is relatively narrow and the fracture process zone is negligibly small, which satisfies the assumption of linear fracture mechanics. The strength limit does not matter since it can always be exceeded, in view of the stress concentration at crack front, and so only fracture energy matters." This theory appeared to be true because both the large scale slab tests and the field section tests from the previous published studies showed RAP-PCC pavement indicated equivalent performance, despite the fact that RAP-PCC had reduced strengths. Hence, the fracture properties of RAP-PCC need to be comprehensively evaluated.
- Durability tests: This study mainly focused on mechanical properties test of PCC containing different types of RAP. While some of the preliminary durability test results are presented, more detailed and systemic research needs to be conducted to verify the RAP-PCC has no durability issues. Those durability tests include but are not limited to:
    - Restricted shrinkage test: The conventional ring test for testing restricted shrinkage (ASTM C1581/C1581M) performed in this study showed no cracking in both reference PCC samples and the RAP-PCC samples within 28 days of curing. In order to get a more significant result, a shrinkage test under more severe conditions such as dual ring test is preferable.
    - Rapid chloride permeability test: The resistivity values of all the studied RAP_PCC mixtures and reference PCC mixtures were determined in this study. Based on the measured resistivity values, all the studied RAP-PCC mixtures showed resistivity values similar to the reference PCC sample. The well-established relationship between resistivity and RCP for PCC with virgin aggregates was used to convert the measured resistivity values to RCP values for the studied RAP-PCC mixtures. However, the RAP-PCC is a new composite whose properties might differ from the conventional PCC. Therefore, it is important to perform the rapid chloride

permeability test to safely verify that the RAP-PCC also has adequate chloride resistance.
    - Chemical durability test: Suitable tests need to be performed to verify any issues related chemical durability. The presence of an asphalt layer in aggregate may reduce the chances of an alkali silica reaction. However, the aggregate in RAP may be reactive sometimes, so detailed alkali silica reaction testing is an important future durability test.
    - Pavement surface characteristics: To have desirable surface characteristics (good abrasion resistance, good skid resistance, good riding quality, and low noise production) is another aspect to determine the feasibility of using RAP-PCC concrete for full-depth application, which is barely investigated in this study. A future study on this aspect is highly needed.
- Field section tests: Field sections using RAP-PCC material shall be built up in Texas as an implementation plan for this study.
    - Full-depth pavement construction: plain PCC full-depth pavement and RAP-PCC full-depth pavements shall be constructed. The determination of the thickness of the plain PCC shall follow the procedures in the TxDOT pavement design manual. The RAP-PCC material shall have desirable surface characteristics; its thickness can be as same as the reference case (plain PCC full-depth). This can verify whether RAP-PCC slab has equivalent performance as the plain PCC equivalent so that the thickness increase is not necessary. Another RAP-PCC full-depth pavement with slab thickness designed according to the design manual can be constructed for the comparison purpose. This RAP-PCC full-depth pavement should have thicker slab than the reference pavement.
    - Two-lift pavement construction: two-lift pavement construction shall be implemented after the necessary future research work is completed. This future work includes:
        - A robust approach to design two-lift pavement needs to be established.
        - The material properties for both top and bottom layers shall be specified.
        - The effect of bonding between top and bottom layer on pavement performance needs to be further studied.
        - Other practical issues on two-lift pavement construction.

After the above-mentioned contents are clear and specified, two-lift pavement that meets the specifications can be constructed. Its performance after a specific time period can be compared with the reference pavement. Figure 101 shows a presentation of the future research work and the implementation plan.

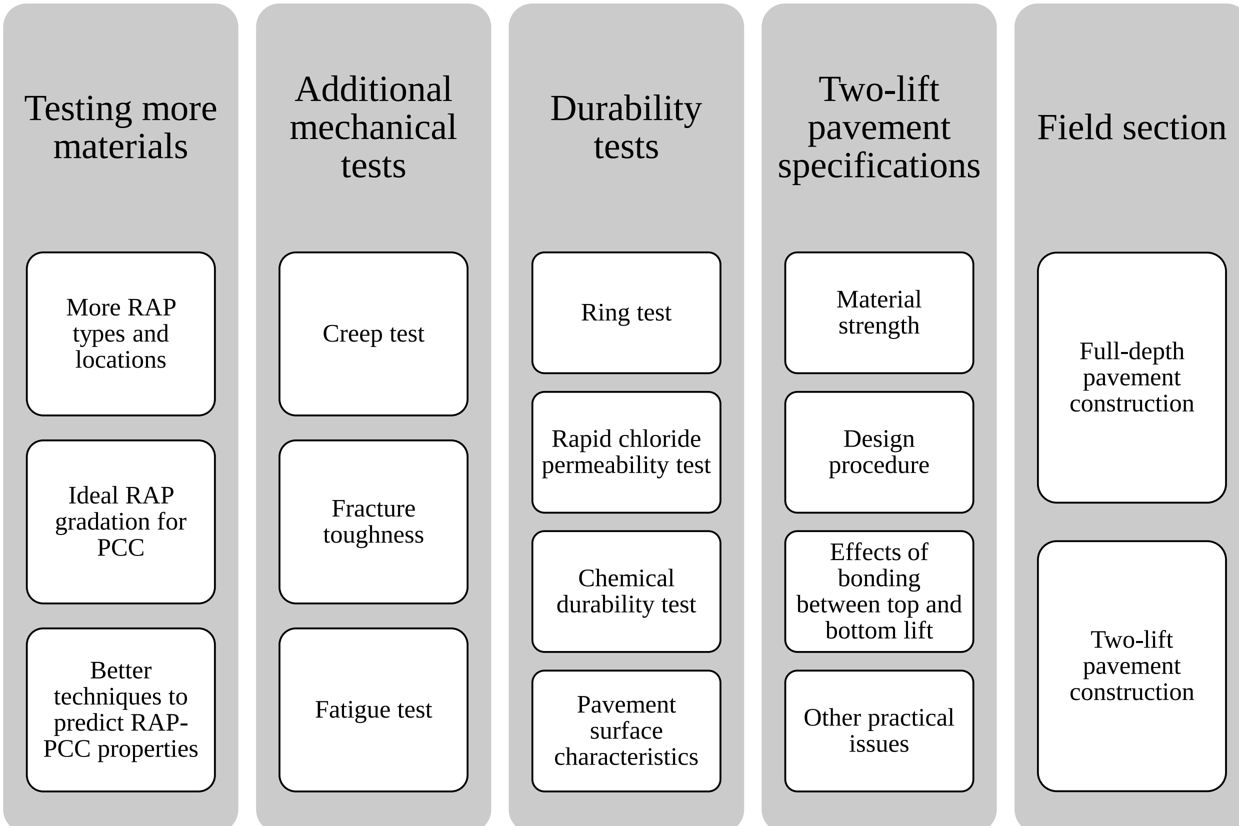


Figure 101. Future Work and Implementation Plan.

CHAPTER 6. CONCLUSIONS

Increasing maintenance and rehabilitation leads to considerable amounts of RAP left in stockpiles in the United States. The possible use of RAP in PCC as aggregate replacement not only would help dispose of excess RAP stockpiles, but also provide a reduction in virgin aggregate consumption in PCC, which brings significant benefits from both economic and environmental standpoints. In this project, the previous findings on the mechanical properties and durability of RAP-PCC reported in the literature were validated. The microstructures and crack propagation in the RAP-PCC system were investigated through several advanced techniques such as optical microscope, x-ray CT, and SEM. Performance evaluation of RAP-PCC slab by using pavement performance software and the life cycle assessment models were also performed. Finally, the guidelines and implementation plan were provided in order to facilitate using PCC containing RAP in the field. The major conclusions from this project are drawn as below.

PROPERTIES OF PCC CONTAINING RAP

One of the major tasks of this project was to validate the earlier findings on mechanical properties and durability of PCC containing coarse RAP. The 0.40_520_HOU, the 0.40_520_BRY, and the 0.40_520_AMA were evaluated through detailed testing. Regression models were developed to predict RAP-PCC mechanical properties with varying asphalt fractions. The model was verified by comparing the results for the 0.40_520_30BRY mix and the 0.40_520_BRY trend lines. The benefit of attaining dense combined aggregate gradation due to the replacement of certain percentage of coarse virgin aggregate by coarse RAP was demonstrated through the detailed testing of 0.40_520_BRY and 0.40_520_35SA mixes. The following conclusions are made:

- Judicious use of coarse RAP with suitable gradation containing sufficient intermediate size particles (>50 percent) ensures dense graded concrete not only because of the large amount of intermediate particles but also because they are less flat and elongated. Presence of an aged asphalt layer in the RAP aggregates provides some additional smoothness, which facilitates better flowability.
- Replacing virgin coarse aggregate by RAP in a typical PCC pavement mix has caused considerable reduction in compressive strength, MOE, and the STS. The percentage reductions of flexural strength for all PCC mixes containing different types of RAPs remain the lowest among all other mechanical properties. RAP replacement exceeding 40 percent was considered impractical in field applications as the percentage reduction of different strengths may not be allowed.
- The rate of reduction in compressive strength was the highest among the tested properties, while the rate of reduction in flexural was the lowest.
- In general, the rate of increase of compressive strength over time for RAP-PCC is lower than the reference mix. The rate of increase of flexural strength over time for RAP-PCC is lower for the 20 percent replacement but higher for the 40 percent replacement, compared to the reference mix.
- Both RAP compressive strength and flexural strength have a strong linear relationship with GABVF, which enables researchers to predict the properties based on regression equations.

- The 0.40_520_30BRY, the 0.40_520_40BRY, and the 0.40_520_35SA turned out to be dense graded RAP concrete mixes. The dense graded RAP concrete mixes showed better workability and mechanical properties compared to the other RAP concrete mixes made with gap graded RAPs (i.e., similar to gap graded virgin aggregates).
- ACI equations were modified to represent the RAP-PCC system and the modified equations were found to be effective to estimate MOE, MOR and STS from measured compressive strength. The methodology to determine optimum RAP replacement level and ideal RAP gradation was developed.
- Based on lab data, PCC concrete made of a certain percentage of coarse RAP (≤40 percent RAP replacement) will not cause any durability issues related to permeability, freeze-thaw resistance, and shrinkage. The preliminary abrasion resistance data (ASTM C 779, Procedure A) shows that RAP-PCC mixes show comparable abrasion resistance property. However, a detailed study on measuring abrasion resistance property of various PAP-PCC mixtures containing RAP from various sources with varying level of replacement (≤40 percent) followed by performance evaluation through modeling is highly warranted to validate whether optimum RAP-PCC mixtures capable of satisfying the requirements for abrasion resistance/skid resistance for pavement applications.

In order to maximize RAP usage, the feasibility of using RAP to produce different classes of concrete of relatively low strength requirements has been evaluated. Researchers analyzed data obtained from the experimental program in this project and the previously published research. Researchers used statistical approaches to generate the correlation between the global asphalt binder volumetric fraction and the percent reduction in compressive strength. With this correlation, the optimum RAP replacement can be estimated. The major findings in this task are summarized:

- The GABVF is a significant independent variable with respect to the dependent variable percent reduction in compressive strength, while the w/cm and cementitious content are insignificant independent variables.
- Logarithmic models are able to describe the relationship between GABVF and the percent reduction in compressive strength. As the trend lines of GABVF versus percent reduction in strength for different curing ages did not vary much, a generalized correlation equation was generated regardless of the curing time of the specimens.
- The optimum RAP replacement for different RAP types was estimated by the generalized correlation equation. An error analysis showed the generalized approach can serve as an approximation (i.e., preliminary estimation) for determining RAP replacement, but a more detailed and case by case study is needed for a project with specific RAP materials.

MICROSTRUCTURES AND CRACK PROPAGATION IN RAP-PCC

Researchers conducted an evaluation of the microstructures and crack propagation in RAP-PCC. Four advanced tools, namely the optical microscope, x-ray CT, SEM, and the microcalorimeter, were used in a combined manner to investigate the mechanisms related to chemical interactions between asphalt and cement hydration and the mechanisms responsible for the mechanical properties observations in this study. The major findings from the investigation are:

- Based on the findings from the RAP-PCC thin section examination, the presence of a clean asphalt layer (i.e., asphalt layer alone without any other particulate materials) around RAP particles was not observed in any of the studied RAP materials. In general, the asphalt layer contains varying amounts of fine aggregates and air voids.
- The presence of RAP clump (i.e., agglomerated RAP particles) in all the studied RAP materials is a common feature. The agglomerated RAP particles appeared to be a single particle to the naked eye, but their agglomerated nature was clearly visible under a microscope.
- Adding RAP into PCC yielded porous ITZ, but the effects on the size and nature of distribution of CH crystals in the ITZ area are minimal.
- The major weak point of the RAP-PCC system is the asphalt. Asphalt cohesive failure (i.e., cracks easily propagate through the asphalt layer around the RAP particles) is the major failure mechanism. The presence of RAP clumps was also found to be other weak zones in RAP-PCC and has some connection depending on the degree of clump formation with the reduction in strengths.
- The presence of RAP has caused higher amounts of air voids in the studied RAP-PCC mixtures compared to the reference PCC sample.

EVALUATION OF RAP-PCC PAVEMENTS

The RAP-PCC pavement performance was evaluated through slab stress analysis and pavement distress analysis by suitable tools. The life cycle assessment of three different pavements was performed through the EIO-LCA model. The following conclusions are made from the findings in this study:

- Using RAP concrete as a PCC layer in pavement yielded reduced maximum tensile stress when no temperature or positive temperature gradients (profile) were assigned. However, the stress/strength was slightly higher due to the low tensile strength of the RAP-PCC.
- At a higher replacement level (>20 percent), the pavement containing RAP-PCC needs slightly higher slab thickness. A slight increase in thickness is largely caused by the increase in CoTE and Poisson's ratio and the reduction in MOR when RAP is added into concrete.
- The decreased MOE of RAP-PCC had positive effects on pavement performance (i.e., reduced IRI and mean joint faulting).
- Compared with the material production for plain PCC pavement, the production of materials for constructing RAP-PCC pavements (either full-depth or two-lift) yielded lower economic activity (more economical) and consumed less energy. It released less air pollutants, greenhouse gases, and toxic materials. It also led to using less land and water.
- The idea of using RAP-PCC as a bottom lift in a two-lift PCC pavement can maximize the RAP usage without compromising the pavement performance or compromise within the permissible limits. The cost and environmental benefits were obvious among all three pavement types.
- Other than the benefits from the material production process, the use of RAP in PCC can reduce the size of the RAP stockpile significantly, which leads to cost savings and protecting the environment and public safety.

GUIDELINES AND IMPLEMENTATION RECOMMENDATIONS

The use of RAP in PCC is largely feasible for the pavement application. Despite the fact that RAP-PCC yielded reduced mechanical properties (especially different strengths), a proper utilization of optimized aggregate gradation benefits from using RAP can compensate the strength reduction and the use of RAP-PCC as a bottom lift in a two-lift pavement construction allows more RAP in the mixture. An even higher amount of aggregates (both coarse and fine) can be replaced to make full use of RAP to make low strength PCC for other applications such as curbs, gutters, sidewalks, etc. In this project, researchers recommended how to properly select RAP material, rationally determine optimum RAP replacement based on different strength criteria, and economically and environmental friendly design pavement structures. Figure 101 presented the implementation and future work of this study.

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APPENDIX A. METHODS FOR CONCRETE AGGREGATE GRADATION OPTIMIZATION

Aggregates are impartible parts of PCC, and they generally occupy 70 percent to 80 percent of the volume of the total mixtures. While numerous investigations have been completed to improve concrete performances by using additives like fibers, supplementary cementitious material, chemical admixtures etc., efforts have also been made to optimize aggregate gradation, and their benefits turned out to be very significant. Because the main purpose of the use of the RAP in this study is as an aggregate replacement for concrete, it is of great importance to review the methods for optimizing aggregate gradation and apply these theories to the mix design in this project. The authors would like to notify here that this section is largely based on Richardson (2005), as he did very good job in searching and summarizing the literature on aggregate gradation optimization.

MAXIMUM DENSITY THEORY

Around 100 years ago, initial researches about gradation optimization were conducted to develop an ideal shape of the gradation curve. The authors at that time believed that aggregate should be graded in size and combined with water and cement to yield the maximum density. This concept could result in mixtures containing fewer voids to be filled with cement paste, leading to higher concrete strength. Talbot and Richart developed the famous equation (Equation A.1) and suggested using n=0.5 to produce maximum density. However, several researches reported difficulties in dealing with concrete made via this method, and eventually the maximum density theory fell into disfavor (Talbot and Richart 1923).

$$P = (\frac{d}{D})^n \qquad \text{Equation A.1}$$

Where
P = amount of material in the system finer than size d.
d = size of the particular group in question.
D = largest particle in the system.
n = exponent governing the distribution of sizes.

SURFACE AREA AND FINENESS MODULUS

Edwards (1918) believed that the surface area of aggregates was a crucial factor to calculate the amount of water required for a workable concrete. Young (1919) further developed this concept and stated that the amount of water is related to the quantity and consistency of cement and the total area of the aggregate. Almost at the same time, Abrams (1918) developed concept for fineness modulus and used this parameter to represent aggregate gradation. Although Abrams insisted his theory was useful and he believed concrete with same fineness modulus would have the same strength, he was continuously being challenged by various researchers (Besson 1935; Edwards 1918; Kennedy 1940; Young 1919).

ACI MIX DESIGN

The ACI method (ACI 1985) was developed largely based on Goldbeck and Grey's work. Their controlling principle stated that workability depends on particle interferences among coarse aggregates. Weymouth developed his theory based on the relationship that one size of particles of one size group are just under the opening provided by the next larger group (Weymouth 1933). The equation can be expressed as Equation A.2:

$$t = [\left(\frac{do}{da}\right)^{\frac{1}{3}} - 1] \times D \qquad \text{Equation A.2}$$

Where
T = average distance between particles of diameter D.
do = density of the size group.
da = ratio of the absolute volume of a size group to the space available t that size in concrete.
D = average diameter of the particles in the size group.

SHILSTONE'S METHOD

Shilstone started to work on concrete aggregate optimization in the 1970s. He believed concrete properties can be controlled by changing aggregate gradation. Shilstone used three fractions different from definition of coarse and fine aggregates in traditional mix design, namely the coarse fraction (Q) (material retained on the 3/8 in. sieve), the intermediate fraction (I) (material passing the 3/8 in. sieve and retained on the #8 sieve), and the fine fraction (W) (material passing the #8 sieve and but coarse than #200 sieve).

IPR CHART

Shilstone promoted to use IPR versus sieve size chart to characterize aggregate gradation (Shilstone Sr 1990). In his theory, a haystack shape curve indicates an ideal gradation, while curves with a double hump may have problems. Figure 102 and Figure 103 show examples of an ideal gradation and a problematic gradation, respectively.

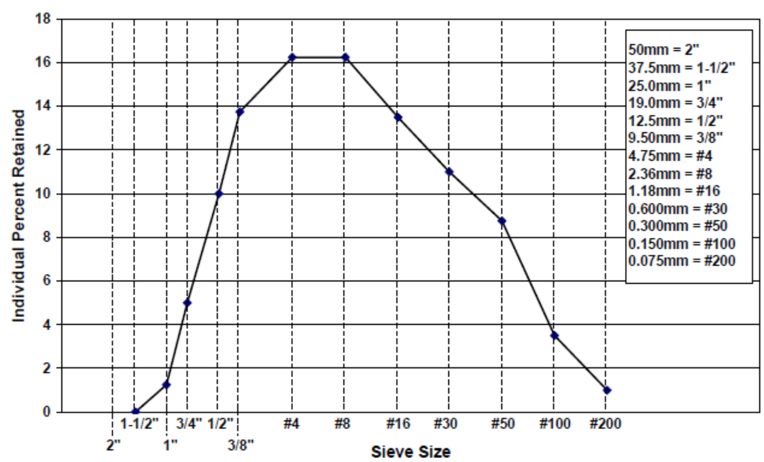


Figure 102. Ideal Haystack Gradation, IPR (Richardson 2005).

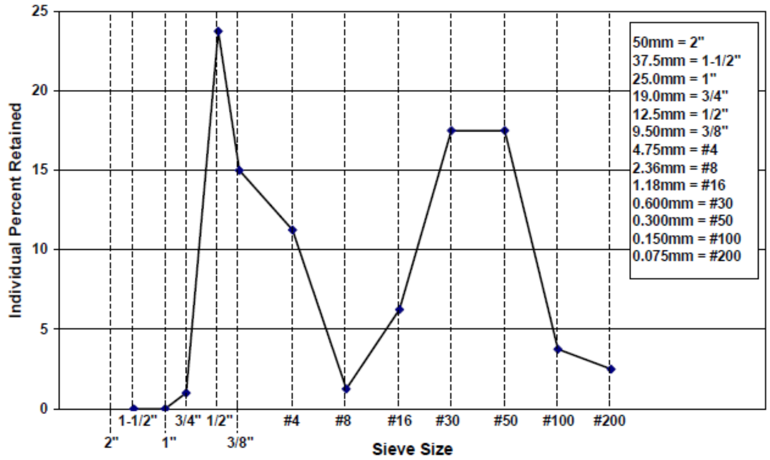


Figure 103. Problematic Gradation, IPR (Richardson 2005).

CF Chart

Two factors were derived from aggregate gradation to predict the workability of concrete mix by Shilstone. CF is defined as Equation A.3, which can be used to represent the proportion of #8 to 3/8 in. aggregate in the total coarse aggregate:

$$CF = [\frac{Q}{Q+1}] \times 100 \qquad \text{Equation A.3}$$

Another term is workability factor (WF), and this is simply percentage aggregate smaller than #8 sieve (coarse than #200). Based on these two factors, Shilstone developed the famous CF chart, and this chart is used to characterize the mix properties, such as hardness, sandiness, excessive shrinkage, degree of gap-grading. Figure 104 presents a revised Shilstone CF Chart. As shown in Figure 104, the chart is divided into five zones representing concrete mixtures of different properties (Richardson 2005):

- Bar: Optimum but excellent control required.
- Zone I: Coarse, gap graded, tends to segregate.
- Zone II: 1-1/2 in., well graded, best spot for everyday mixes.
- II-1: excellent but caution.
- II-2: excellent paving but slipform.
- II-3: high quality slab.
- II-4: good general.
- II-5: varies to material and construction needs.
- Zone III: ¾ in. and finer.
- Zone IV: Oversanded, sticky.
- Zone V: Rocky.

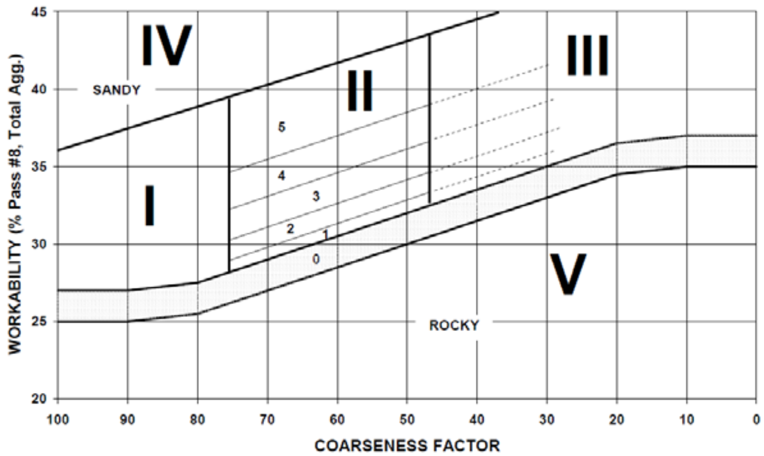


Figure 104. Revised Shilstone CF Chart (Shilstone and Shilstone Sr 1997).

0.45 Power Chart

Shilstone also plotted the aggregate gradation on a 0.45 power plot, as shown in Figure 105.

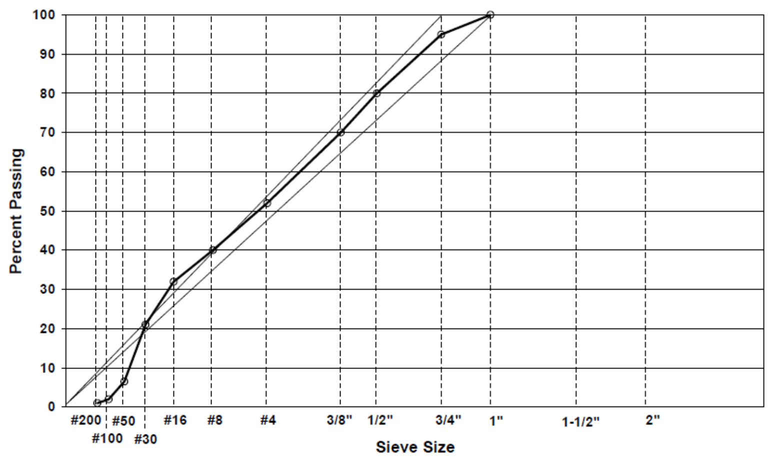


Figure 105. Shilstone's 0.45 Power Chart.

In the chart, the maximum density line is drawn from the origin to the intersection of the 100 percent passing line with either the nominal maximum size or the maximum size. A gradation following the maximum density line down to either the #8 (Shilstone and Shilstone Sr) sieve or the #16 (Shilstone 1993) sieve where it dips below the reference line is considered to be optimum.

Recommendations Based on Shilstone Method

Holland (Holland 1990) first came up the ideas to specify an "8-18" band in IPR chart, meaning the total percentage of fine and coarse aggregate on any size should be between 8 and 18 percent. Harrison (Harrison 2004) suggested to use IRP and CF charts for optimization. He developed an optimum location on CF chart for slabs-on-ground (Figure 106).

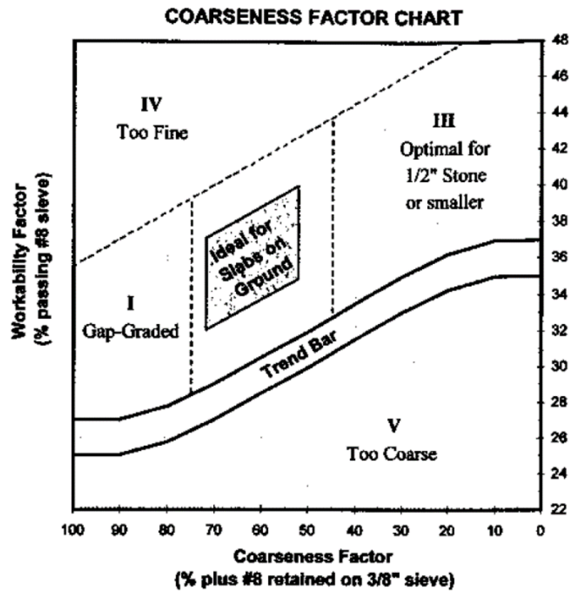


Figure 106. Optimum Location on CF Chart for Slabs-on-Ground (Harrison 2004).

The U.S. Air Force adopted Shilstone's design concepts and developed their specification guide. In the guide, the IPR chart with 8-18 band, modified CF chart, and 0.45 power chart are required to be used. The intention to use the band in IPR chart is to control individual retained percent between 8 and 18 for sieve #30 through one size below nominal maximum size, and keep other sizes below 18 percent. Also, a significant valley (one has more than two sieve sizes between two peaks) is not allowed in the plot. Figure 107 and Figure 108 give examples for an acceptable plot and an unacceptable one. For the CF chart with construction-related areas (Figure 109), the U.S. Air Force concentrates the Shilstone chart between CF value 30 and 80. They modified Zone II in Shilstone's chart and replaced the five strip areas with three circular areas, which are recommended locations for slip from (A) paving, (B) form and place mechanical paving, and (C) hand replacement. The 0.45 chart (Figure 110) in their manual is used to check the gradation if doubts still remain after the use of the IPR and CF chart. Three references line are plotted in the chart, and a good gradation should meander along the top size line.

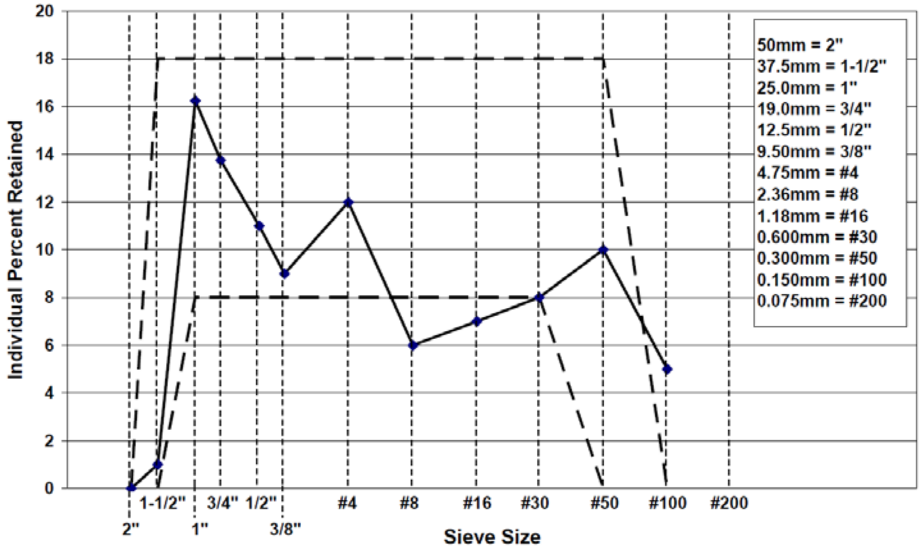


Figure 107. Example of an Acceptable Mix for U.S. Air Force Design.

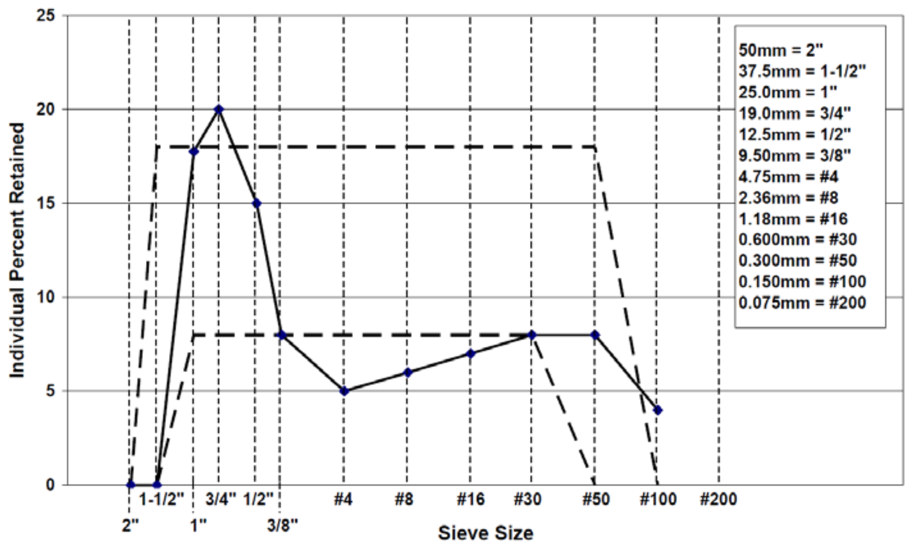


Figure 108. Example of an Unacceptable Mix for U.S. Air Force Design.

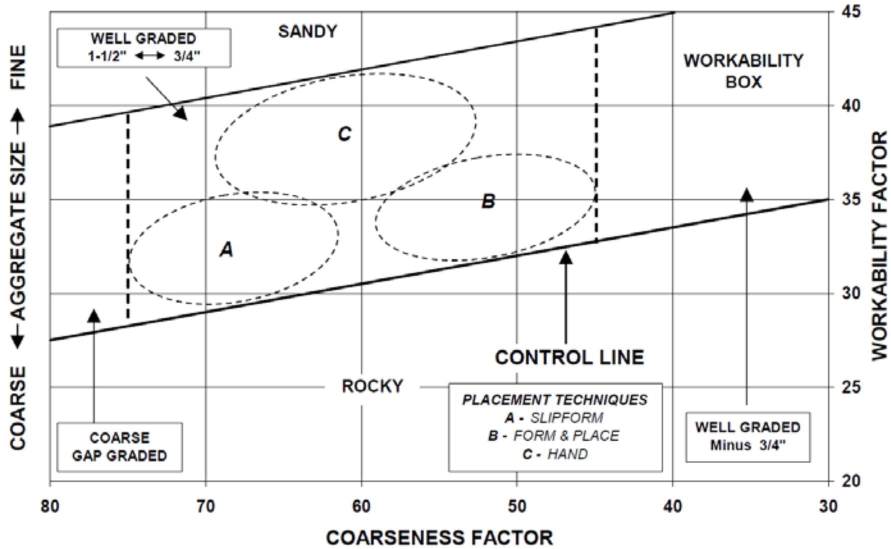


Figure 109. U.S. Air Force Aggregate Proportioning Guide with Construction Related Areas.

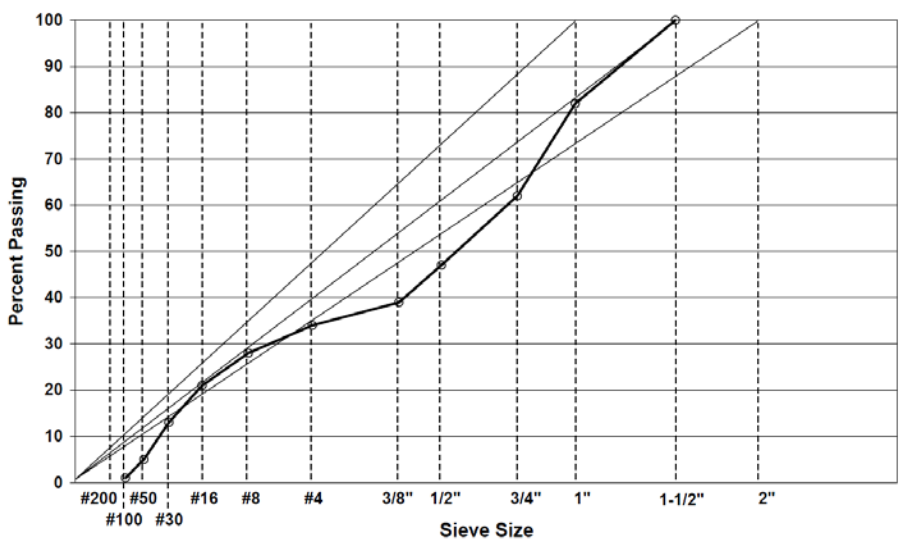


Figure 110. U.S. Air Force 0.45 Power Chart.

APPENDIX B. RESULTS OF EMAIL SURVEY: DIFFERENT TEXAS DISTRICT INTEREST ON USING RAP IN PCC

Table 48 shows the results of the email survey.

Table 48 Email Survey Results.

District	Production	Demand in HMA	Left in stockpile	Interest in application for PCC	Rock type	Contact Information
Atlanta	Low and sporadic	High	Low	Yes		Miles Garrison Miles.Garrison@txdot.gov
San Antonio				Yes	Mostly limestone	Brett Haggerty Brett.Haggerty@txdot.gov
Brownwood	Low		Low	Yes	Typically limestone RAP	Eric Lykins eric.lykins@txdot.gov
Houston	High	Limited	Mediate	Yes	Crushed limestone, gravel particles	Stanley Yin Stanley.Yin@txdot.gov
Bryan				Yes	limestone	Jennifer Mascheck Jennifer.Mascheck@txdot.gov
Amarillo				Yes	Gravel , Important	Buster Sanders Buster.Sanders@txdot.gov
Austin				No	Limestone and gravel	Elizabeth Lukefahr elizabeth.lukefahr@txdot.gov
Waco	High	High		No	Limestone and gravel	Billy Pigg Billy.Pigg@txdot.gov
Odessa				No	Limestone and rhyolite	KC Evans kc.evans@txdot.gov
Lufkin	Low	High	Low	No		Richard Boles-Gracia richard.bolesgracia@txdot.gov
El Paso	Low		Low	No	limestone and granite	Aldo Madrid aldo.madrid@txdot.gov
Wichita Falls				No	Nearly limestone	Mark Smith mark.smith@txdot.gov
Childress					Gravel or granite	Darwin Lankford darwin.lankford@txdot.gov
Lubbock					Gravel	Darral Bryant darral.bryant@txdot.gov
Fort Worth					Non-limestone	Richard Williammee Richard.Williammee@txdot.gov

APPENDIX C. SELECTIVE TESTS TO COMPARE MORE RIGOROUS CLASS P MIXES AND LESS RIGOROUS CLASS P MIXES

The designed class P concrete in this research (the 0.40_520 series) adopted a #4 coarse aggregate gradation instead of using a #2 or #3 gradation which is specified in Texas Standard Specifications. Because there is a little difference between the #3 and #4 gradation, it was expected that the difference in terms of mechanical properties (i.e., compressive strength, flexural strength) between mixes made with #3 coarse aggregate (considered as more rigorous class P mixes) and those made with #4 coarse aggregate (considered as less rigorous class P mixes) are not significant, either. To verify this assumption, a set of RAP-PCC samples made with #3 virgin aggregate gradation was tested. Table 49 shows the strength comparison between the mixes made with #3 coarse aggregate and those made with #4 coarse aggregate. Table 49 clearly shows the differences between the two sets of mixes were insignificant (with a same order of coefficient of variance of the tests). Therefore, what has been concluded regarding the RAP-PCC strengths analysis is considered valid for the more rigorous class P mixes.

Table 49. Comparison of Selected Mechanical Properties between RAP-PCC Made with #3 Virgin Coarse Aggregate and RAP-PCC Made with #4 Virgin Coarse Aggregate.

Sample	Slump	Air Void (%)	fc (psi)		MOE ($\times 10^6$ psi)		MOR (psi)		STS (psi)	
			7-day	28-day	7-day	28-day	7-day	28-day	7-day	28-day
0.40_520_40SA	2.5	3.0	2698 (7%)*	3911 (4%)	3.279 (3%)	3.79 (3%)	475 (8%)	574 (2%)	463 (3%)	569 (7%)
0.40_520_40SA-#3	3.0	3.5	2731 (5%)	3682 (2%)	3.305 (2%)	3.55 (7%)	501 (4%)	577 (0.1%)	443 (6%)	558 (0.4%)
Difference (%)	-	-	-1.22%	+6.20%	-0.76%	+6.73%	-5.10%	-0.46%	+4.29%	+1.91%

*The coefficient of variance is shown in the bracket.

APPENDIX D. RAP-PCC TRIAL MIXES TEST (THE 0.45_656_HOU SERIES)

A series of trial mixes with 0.45 water/cementitious (w/cm) ratio and 656 lb/cy cementitious content was initially designed. Table 50 presents the mix designs for the trial mixes. The 656 lb/cy cementitious content was still within the TxDOT specification for class P concrete. The class F fly ash was added to replace 20 percent of cement on the weight basis. The amount of mid-range water reducer added was 2 oz/100 lb of cementitious materials, and the amount of air entraining agent was selected as 0.3 oz/100 lb of cementitious to get an air content of 5.0 percent. In this trial mixes, only HOU_C was introduced into the mix as a virgin coarse aggregate replacement. The replacement levels for the trial mix were selected as 20 percent, 40 percent, 70 percent, and 100 percent, and all of them were on the volumetric fraction of the total coarse aggregate. The mix ID in this project was assigned with the following format:

w/cm_cementitious content_replacement level+RAP type

Example: 0.45_656_40HOU represents a mix that has 0.45 w/cm ratio, 656 lb/cy cementitious content, and HOU RAP to replace 40 percent of virgin coarse aggregate.

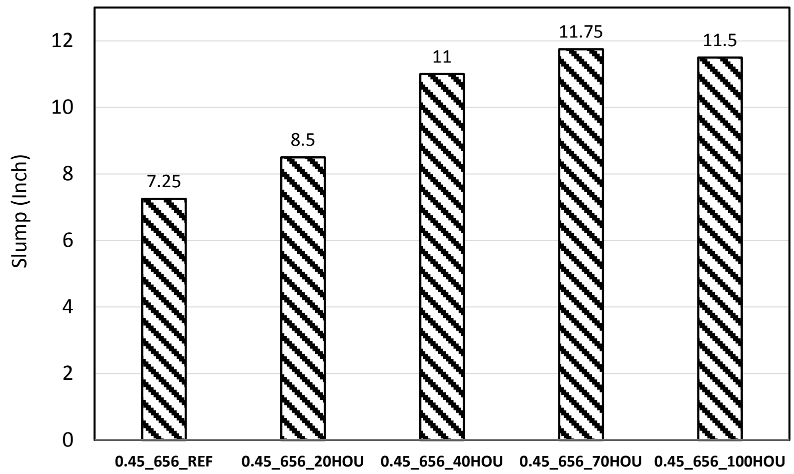
Table 50. Mix Design for the 0.45_656 Mixes.

	0.45_656_REF	0.45_656_20HOU	0.45_656_40HOU	0.45_656_70HOU	0.45_656_100HOU
Cement (lb/cy)	525	525	525	525	525
Fly Ash (lb/cy)	131	131	131	131	131
Virgin coarse aggregate (lb/cy)	1783	1394	1021	493	0
RAP (lb/cy)	0	349	681	1149	1582
FA (lb/cy)	934	961	988	1029	1071
Water Reducer (fl oz/cy)	13.1	13.1	13.1	13.1	13.1
Air Entraining Agent (fl oz/cy)	1.968	1.968	1.968	1.968	1.968
Water (lb/cy)	295	295	295	295	295

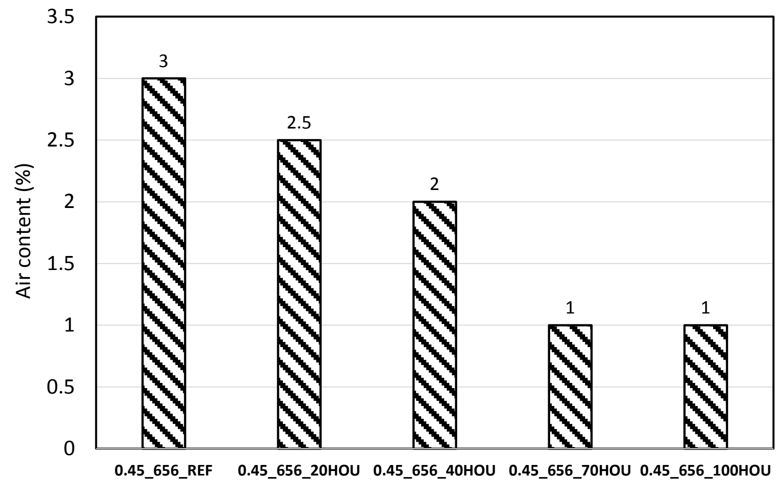
The fresh concrete properties (i.e., slump and air content) and the 7-day, 28-day and 56-day hardened concrete properties (i.e., compressive strength, MOE, flexural strength and STS) were tested according to the corresponding standards. The test results are presented below.

FRESH CONCRETE TEST RESULTS

Figure 111 shows the results for the slump and air content of the 0.45_656 series. From Figure 111(a), replacing virgin coarse aggregate by HOU_C with varying replacement levels increased the mix slump significantly. When the RAP replacement level ≥40 percent, the slump became extremely high. There is no doubt that such a high slump would result in serious segregation problem, so a more reasonable w/cm ratio (0.40) and cementitious content (520 lb/cy) were used in the modified mix design for the detailed testing. Figure 111(b) shows a decreasing trend of air content with increasing levels of RAP replacement in the mix.



(a) Slump measurement



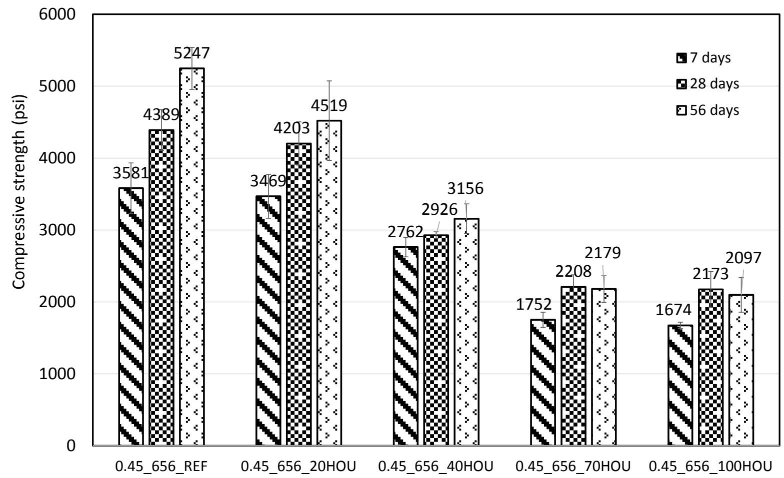
(b) Air content measurement

Figure 111. Fresh Properties of 0.45_656_HOU Mixes.

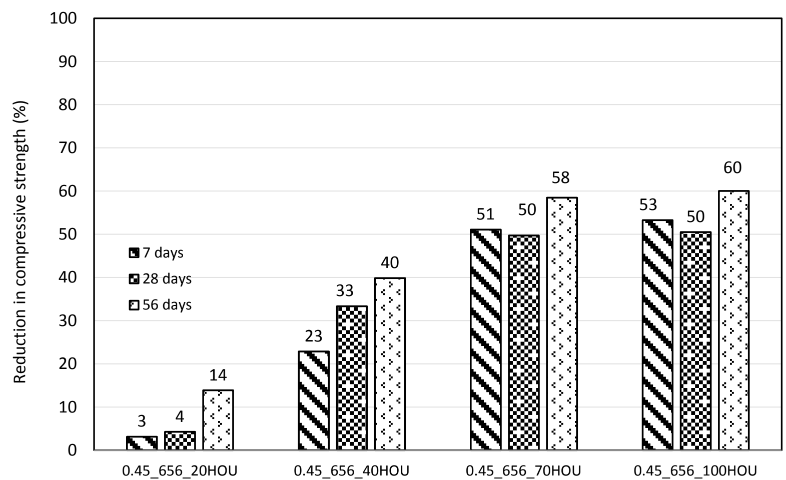
HARDENED CONCRETE TEST RESULTS

Compressive Strength

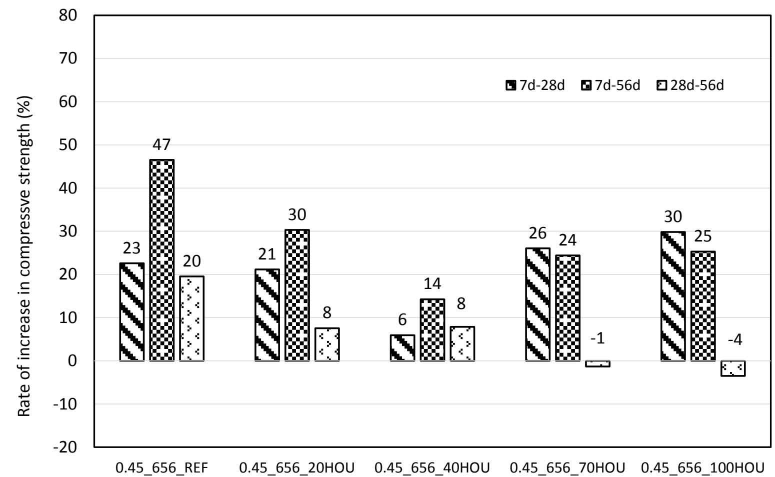
Figure 112 plots the absolute compressive strength values, the percentage reduction of strength in comparison with reference mix and the rate of increase of strength over time. Results show that the higher the amount of RAP in the mix, the higher the reduction of the compressive strength is irrespective of testing age. Figure 112(b) shows that RAP replacement of 70 percent and 100 percent has caused more than 50 percent reduction in compressive strength in comparison with the reference mix. Therefore, RAP replacement more than 40 percent is considered to be impractical in the field. Based on the literature review on previous research (presented in Chapter 1), the other researchers have also recommended the similar practical level of RAP replacement (Brand 2012). As a result, researchers decided to limit the RAP replacement level ≤ 40 percent for all follow-up detailed testing. Regarding the rate of strength increase (Figure 112(c)), almost all the samples had higher strength improvement from 7 day to 28 day than 28 day to 56 day, and when the RAP replacement were at high levels (i.e., 70–100 percent), the strength increase from 28 days to 56 days became negligible. The rate of compressive strength increase over time (7 to 56 days) for the RAP concrete (irrespective of replacement level) is invariably lower than that at reference concrete.



(a) Compressive strength



(b) Percentage reduction in comparison with the reference mix

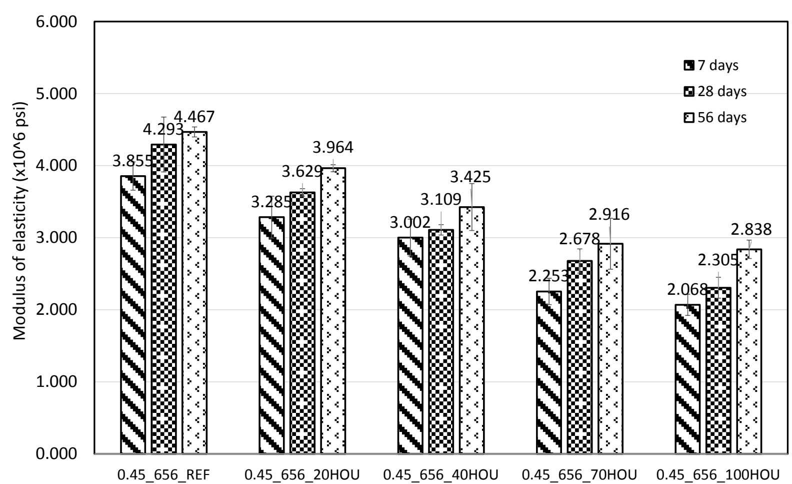


(c)Rate of increase over different time intervals

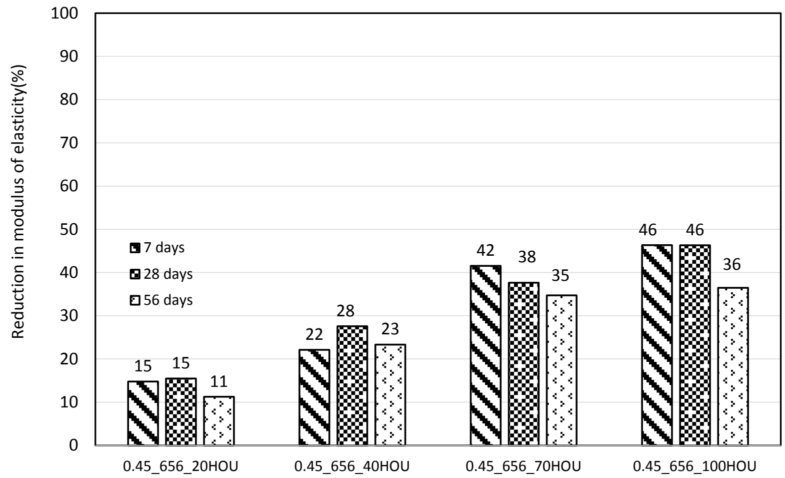
Figure 112. Compressive Strength Results for 0.45_656_HOU Mixes.

Modulus of Elasticity

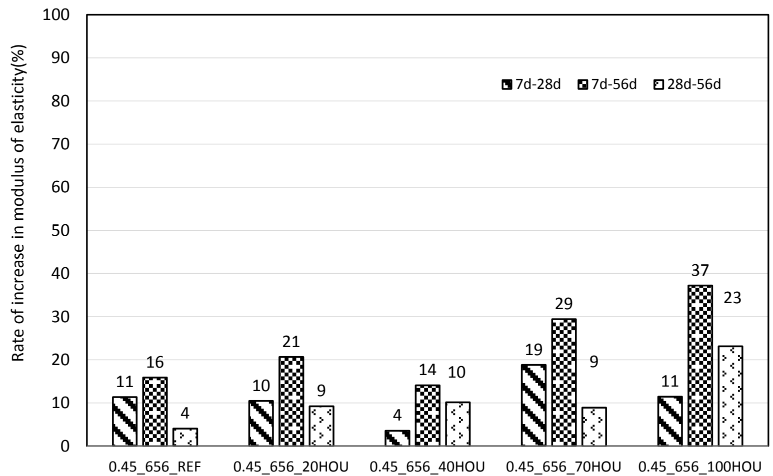
Figure 113 plots the absolute MOE values, the percentage reduction of MOE in comparison with the reference mix, and the rate of increase of MOE over time. The inclusion of RAP with varying replacement levels in the concrete mix reduced the MOE dramatically (Figure 113(a)). Especially when the replacement level exceeded 40 percent, the reduction of MOE was found to be more than 35 percent (Figure 113(b)). For the rate of increase of MOE over time, a clear trend was not obtained. Although the absolute value of RAP concrete MOE is lower than reference concrete, the rate of increase of MOE over time is either comparable or even greater in RAP concrete than the reference concrete.



(a) MOE



(b) Percentage reduction in comparison with the reference mix

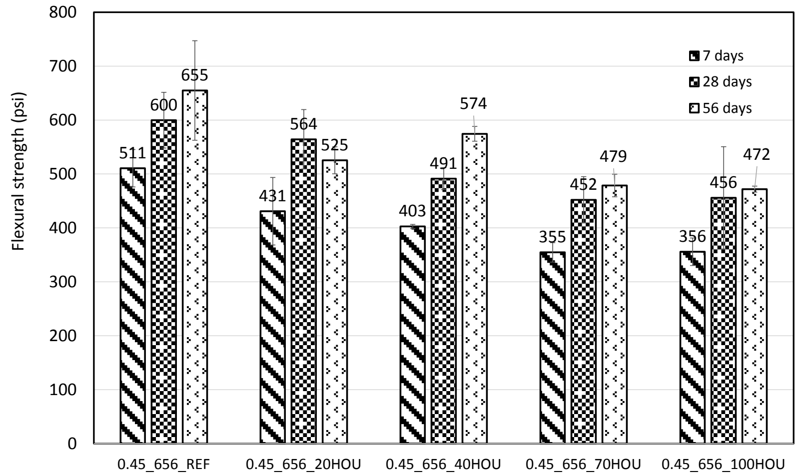


(c) Rate of increase over different time intervals

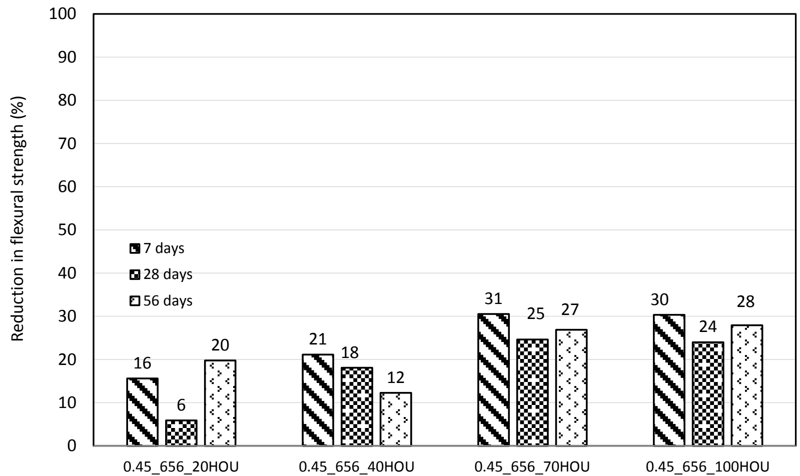
Figure 113. MOE Results for 0.45_656_HOU Mixes.

Flexural Strength

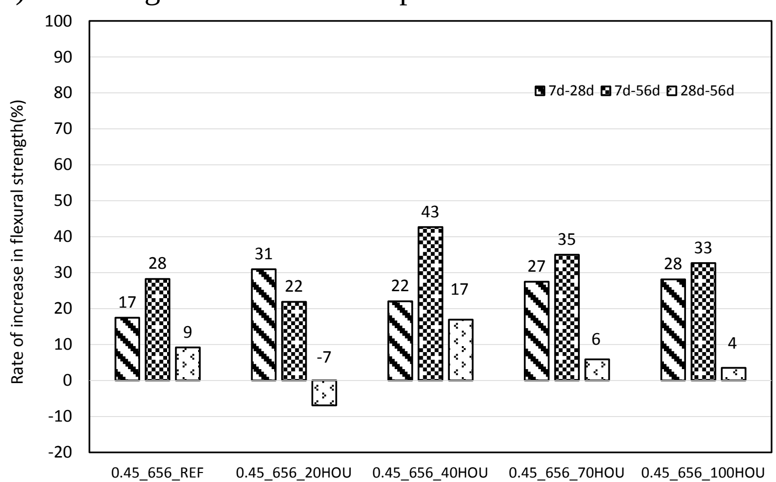
Figure 114 shows the absolute values of MOR, the percentage reduction of MOR in comparison with the reference mix, and the rate of increase of MOR over time. Unlike other mechanical properties, the reduction of MOR for concrete containing RAP was not that significant. The flexural strength of the concrete mix with RAP replacement level of 70 percent was similar with that of concrete mix with 100 percent RAP replacement. This indicates the flexural strength may not be affected by RAP content when the replacement level exceeded a limit. Figure 114(c) shows that more flexural strength improvement occurred in the time period of 7 day to 28 days than that between 28 days and 56 days. The rate of increase of MOR of RAP concrete (7–28 and 7–56 days irrespective of replacement levels) is in general higher than that at the reference concrete.



(a) Flexural strength



(b) Percentage reduction in comparison with the reference mix

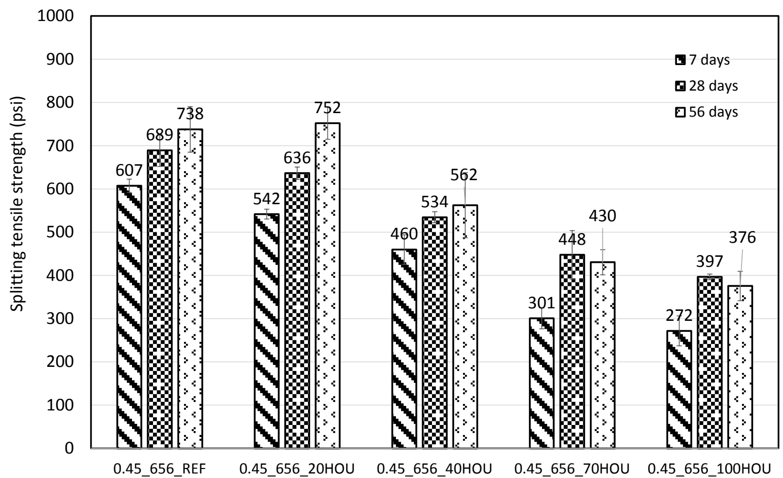


(c) Rate of increase over different time intervals

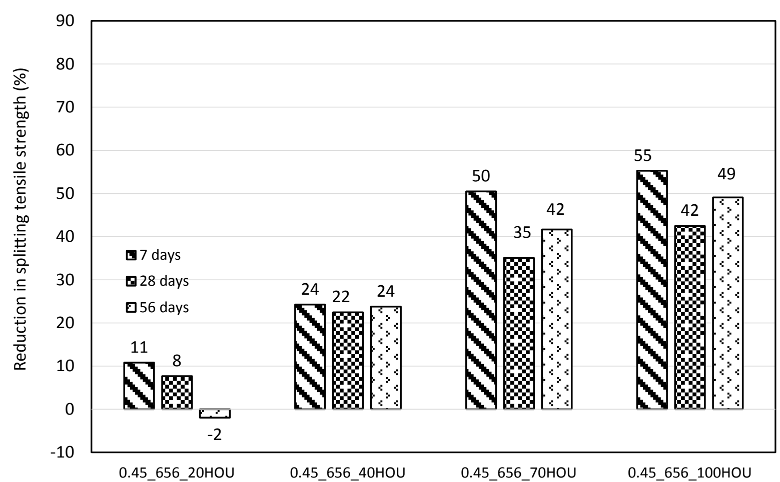
Figure 114. Flexural Strength Results for 0.45_656_HOU Mixes.

Splitting Tensile Strength

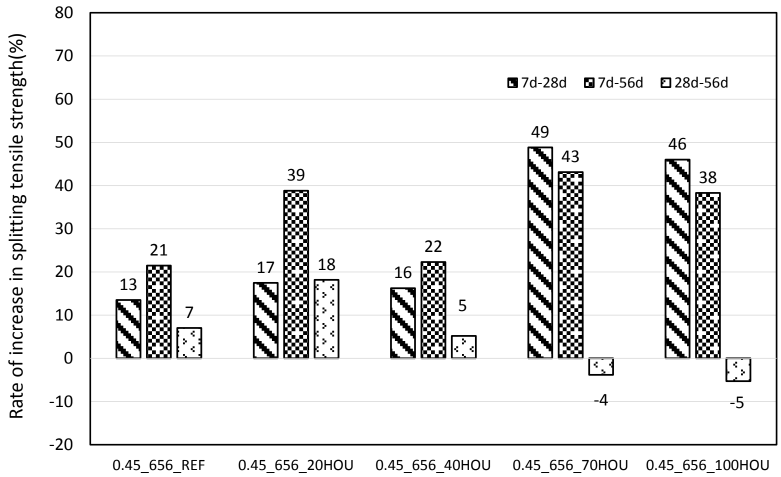
Figure 115(a) compares the absolute values of STS, and Figure 115(b) shows the rate of reduction of STS in comparison with the reference concrete. Similar to the results for the compressive strength and MOE, the reduction in STS was significant, especially at the high replacement levels (i.e., 70 percent and 100 percent). Figure 115(c) indicates the STS improved faster during short term than it did during long term. The rate of increase of STS for the RAP concrete mixes (7–28 and 7–56 days, irrespective of level of replacement) is greater than that at the reference concrete (Figure 115(c)).



(a) STS



(b) Percentage reduction in comparison with the reference mix



(c) Rate of increase over different time intervals

Figure 115. STS for 0.45_656_HOU Mixes.

FINDINGS FROM THE TRIAL MIXES

The following conclusions are made based on the results from the 0.45_656_HOU series:

- A combination of 0.45 w/cm and 656 lb/cy cementitious content led to extremely high slumps for the RAP concrete mixes, especially at high RAP replacement level, causing potential segregation issues.
- RAP replacement exceeded 40 percent caused very significant reduction in concrete mechanical properties (especially for compressive strengths, MOE, STS).
- Unlike other mechanical properties, the reduction of MOR for concrete containing RAP was not that significant.
- The rate of increase of MOR, MOE, and STS for the RAP concrete mixes (7–28 and 7–56 days, irrespective of level of replacement) is greater than that at the reference concrete.

It was recommended that reduction of w/cm and cementitious content to 0.40 and 520 lb/cy respectively, will facilitate to overcome the above limitations. Therefore, a 0.40_520 RAP-PCC series with RAP replacement level up to 40 percent warranted further detailed testing.