

Fresh and Hardened Properties of Concrete with Fractionated Reclaimed Asphalt Pavement

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Abstract

A study was completed to investigate the changes in fresh and hardened properties when using coarse, fractionated reclaimed asphalt pavement (FRAP) as a partial replacement of virgin coarse aggregate in a ternary blended concrete. The FRAP replacement levels were 0, 20, 35, and 50%. The ternary blended concrete consisted of 65% Type I Portland cement, 25% Grade 100 ground granulated blast furnace slag, and 10% Class C fly ash. Two coarse FRAP sources were investigated: one washed (16 mm maximum size) and one dirty (12.5 mm maximum size). The dirty FRAP source was additionally processed in the laboratory by washing and sieving over a 4.75 mm sieve to reduce the amount of fines and agglomerated sand/asphalt particles. The fresh concrete properties showed that adding FRAP had little to no effect on the air content, increased the slump, and reduced the unit weight. The fresh and hardened concrete characteristics (compressive, split tensile, and flexural strength) demonstrated that replacement levels up to 35% FRAP could be utilized without compromising existing concrete material specifications for paving. Surprisingly, washing the coarse dirty FRAP did not provide any strength benefit over the dirty, unprocessed FRAP for the sources evaluated.

Key words: reclaimed asphalt pavement, RAP, fractionated reclaimed asphalt pavement, FRAP, recycling, ternary concrete, slag, fly ash, sustainability, green concrete

Introduction

The Illinois State Toll Highway Authority (The Tollway) and other agencies have stockpiled large amounts of reclaimed asphalt pavement (RAP) from pavement rehabilitation projects around the Chicago metropolitan area. RAP taken off the Tollway mainlines is considered high quality because the original asphalt pavements used high quality crushed coarse aggregate as well as manufactured sands rather than natural sand. The Tollway additionally processes the millings to create fractionated reclaimed asphalt pavement (FRAP) in which two screens are used to separate the coarse and fine portions of the material to better control gradation and to minimize dust. Agglomerated particles with sizes greater than the maximum screen, typically 1/2 inch (12.5 mm) or 5/8 inch (16 mm), are discarded. Both coarse and fine FRAP replacements have proven to be effective in hot mix asphalt (HMA) mixtures (Vavrik

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et al. 2008). Within the past several years, the Tollway has successfully replaced up to 35% of the liquid asphalt binder in almost all of the mainline surface course HMA overlay mixes by using fine FRAP particles (4.75 mm maximum size) combined with reclaimed asphalt shingles. This has resulted in large stockpiles of coarse FRAP (>4.75 mm size). In 2010, the Tollway cast an experimental HMA-concrete (flexible over rigid) composite pavement ramp with 35% coarse FRAP replacement in the concrete mix to explore this future option.

The objective of this study was to determine the viability of using the coarse portion of a washed or dirty FRAP as a partial replacement of virgin coarse aggregate in a ternary blended concrete containing cement, slag, and fly ash. The concrete with FRAP is a more sustainable solution, both environmentally and economically, for future concrete rehabilitation projects on the Tollway due to its utilization of by-product cementitious materials (i.e. slag, fly ash) and the existing stockpiles of FRAP.

Previous studies have found that the inclusion of RAP as an aggregate into concrete will adversely affect the hardened properties of the concrete. The results from Delwar et al. (1997) indicate a greater than 50% reduction in compressive strength when using 100% coarse RAP and about a 70% reduction when using 100% coarse and fine RAP. For a 50 MPa (7250 psi) mix, Al-Oraimi et al. (2009) found a compressive strength reduction of about 55% when using 100% coarse RAP and a loss of around 35% when using 50% coarse FRAP. Using 100% coarse RAP, Hassan et al. (2000) found a 65% reduction in compressive strength and a 35% reduction in flexural strength at 28 days. Testing different mix designs, Hossiney et al. (2010) found a reduction of 45-60% in the compressive strength at 14 days and a reduction of about 20-30% in the flexural strength at 14 days when using 40% coarse RAP. Other studies have reported variation in the concrete compressive strength loss as the proportion of RAP (either coarse or both coarse and fine) replacement increased (Kolias 1996, Sommer and Bohrn 1998, Dumitru et al. 1999, Mathias et al. 2004, Huang et al. 2005, Huang et al. 2006, Hossiney et al. 2008, Okafor 2010, Bilodeau et al. 2011). Likewise, as the RAP content increases, the split tensile strength has shown to decrease (Kolias 1996, Sommer and Bohrn 1998, Mathias et al. 2004, Huang et al. 2005, 2006, Hossiney et al. 2008, Hossiney et al. 2010, Bilodeau et al. 2011), and the flexural strength also decreases with increasing RAP replacement (Sommer 1994, Kolias 1996, Sommer and Bohrn 1998, Hassan et al. 2000, Hossiney et al. 2008, Al-Oraimi et al. 2009, Hossiney et al. 2010, Okafor 2010). None of studies listed above specified the process used to obtain the coarse or fine RAP gradations and thus it is assumed that the materials were not fractionated or washed prior to casting in the concrete.

The existing literature suggests that a maximum replacement of the coarse aggregate fraction of 20-25% may be possible without lowering the existing design standards for concrete pavement (especially strength), and that replacements up to 50% may be feasible if the concrete is properly proportioned. Sommer (1994) suggested that 10% RAP in the coarse aggregate fraction would not be significantly detrimental and 20% RAP would only slightly reduce the flexural strength. Finally, no literature has been found that compared processing or sizing techniques for RAP, such as washing or secondary screenings, on improving the concrete strength properties.

Considering the fresh properties of the concrete, the results reported in the literature are variable and make it difficult to render definitive conclusions. With the inclusion of RAP (coarse and/or fine) to the concrete, the slump has been found to decrease (Delwar et al. 1997, Hossiney et al. 2008, Al-Oraimi et al. 2009, Okafor 2010), increase (Hossiney et al. 2010) or have variable results (Huang et al. 2005,

2006). By replacing virgin aggregate with RAP, the air content of the concrete been shown to increase (Delwar et al. 1997), not significantly change (Huang et al. 2005, Huang et al. 2006, Hossiney et al. 2010), or have variable results (Hossiney et al. 2008). Finally, the concrete unit weight has been found to decrease with added RAP (Delwar et al. 1997, Hossiney et al. 2008, Al-Oraimi et al. 2009, Hossiney et al. 2010).

Properties and Proportions of Washed and Dirty FRAP Concrete

Two different FRAP sources taken off the Jane Addams Memorial Tollway (I-90) were used in this investigation with the main part of the study examining a coarser (5/8 inch, 16 mm, maximum size) washed, “clean” FRAP (known hereafter simply as FRAP) and the secondary study examined another coarse graded (1/2 inch, 12.5 mm, maximum size) unprocessed, unwashed, “dirty” FRAP (labeled hereafter as dirty FRAP). In the second study, the dirty FRAP was further processed in the laboratory by two methods: washing over a #4 (4.75 mm) sieve and dry sieving to remove particles passing the #4 (4.75 mm) sieve. Visual comparisons of the FRAP and dirty FRAP can be seen in Figure 1. The main objective of the secondary study was to determine the effects of additional finer FRAP and agglomerated sand/asphalt particles on the concrete strength properties and to ascertain if additional processing of the FRAP is necessary.

Table 1. Aggregate Properties and Particle Size Distribution

	FRAP	Dirty FRAP	Washed/ Sieved Dirty FRAP	Virgin Coarse Aggregate	Sand1²	Sand2³
Bulk Unit Weight, lb/ft ³ (kg/m ³)	93.4 (1500)	90.1 (1440)	-	96.9 (1550)	112.1 (1800)	108.7 (1740)
Relative Specific Gravity (SSD) ¹	2.59	2.56	-	2.72	2.66	2.51
Absorption	2.45%	1.79%	-	1.80%	1.47%	2.00%
Asphalt Content	2.1%	-	-	-	-	-
Agglomerated Particles	14.2%	20.4%	-	-	-	-
Gradation						
1" (25mm)	100.0%	100.0%	100.0%	100.0%	-	-
3/4" (19mm)	99.9%	100.0%	100.0%	96.2%	-	-
1/2" (12.5mm)	78.4%	99.3%	99.4%	36.5%	-	-
3/8" (9.5mm)	37.9%	86.3%	82.7%	11.1%	100.0%	100.0%
#4 (4.75mm)	3.6%	21.9%	4.5%	1.3%	99.9%	95.1%
#8 (2.36mm)	1.6%	5.5%	0.2%	1.1%	90.1%	88.6%
#16 (1.18mm)	1.1%	2.8%	0.1%	1.1%	70.3%	78.9%
#30 (0.6mm)	0.8%	1.9%	0.1%	1.1%	46.4%	66.4%
#50 (0.3mm)	0.6%	1.3%	0.1%	1.0%	16.4%	25.6%
#100 (0.15mm)	0.3%	0.7%	0.1%	0.9%	3.2%	5.4%
#200 (0.075mm)	0.1%	0.3%	0.0%	0.7%	0.8%	1.6%

¹ SSD = Saturated Surface Dry

² Sand1 is used with the FRAP mixes

³ Sand2 is used with the dirty FRAP mixes

The coarse FRAP replaced the virgin coarse aggregate at levels of 0, 20, 35, and 50%. The same virgin coarse aggregate was used in both the primary and secondary studies but a different natural sand source was used in the primary and secondary studies. As presented in Table 1, specific gravity and unit weight of the FRAP are less than that of the virgin coarse aggregate. The dirty FRAP had a finer gradation, particularly at the 1/2-inch (12.5 mm) sieve. Therefore, the various concrete mixtures with various levels of FRAP replacement of the coarse aggregate did not produce the same combined aggregate gradation.

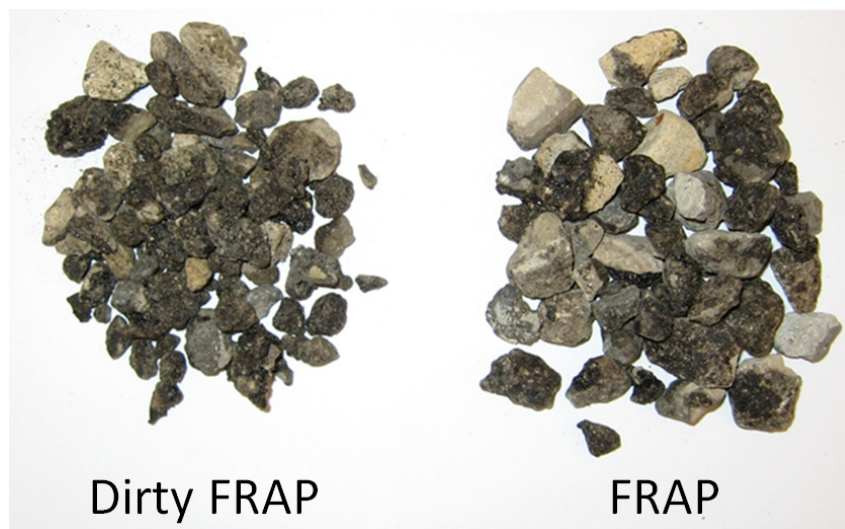


Figure 1. Visual comparisons of the dirty FRAP and FRAP.

The ternary concrete mixture can be found in Table 2. The concrete with FRAP contained a total of 630 lb/yd³ (374 kg/m³) cementitious materials in a mix with 65% Type I Portland cement, 25% Grade 100 ground granulated blast furnace slag, and 10% Class C fly ash. The water-to-cementitious ratio (w/cm) was maintained at 0.37 for all mixes. For comparison, standard Illinois Department of Transportation (IDOT) concrete mixes for pavements typically contain 565 to 605 lb/yd³ (335 to 359 kg/m³) of cementitious material with a w/cm ratio of 0.40 to 0.44. In each mix, the amount of water was adjusted for the current moisture state of each aggregate to ensure that there was sufficient water to bring the aggregate to saturated surface dry condition. In addition, two chemical admixtures were utilized: an air-entraining admixture (AEA) and a water reducing admixture (WRDA). These were added to produce a workable concrete (2-3 inch, 50-75 mm, slump) for placement and sufficient air voids (5-8%) to minimize freeze/thaw damage. The concrete was mixed in accordance ASTM C192 (2007). The coarse aggregates were mixed with about one-third of the water (dosed with the AEA) and mixed for 30 seconds. The sand and cementitious materials were added, and while the mixer was turning, the remaining water was slowly added and then mixed for three minutes. During this initial three minutes of mixing the WRDA was added slowly to the concrete. The mixture was allowed to rest three minutes before a final mixing of two minutes.

Table 2. Mixture Design Proportions in lb/yd³ (kg/m³)

	FRAP				Dirty FRAP			
	0%	20%	35%	50%	0%	20%	35%	50%
Cement	409.5 (242.8)							
Slag	157.5 (93.4)							
Fly Ash	63.0 (37.4)							
Virgin Coarse Aggregate (SSD)	1895.4 (1124.0)	1501.2 (890.2)	1210.7 (718.0)	924.5 (548.2)	1895.4 (1124.0)	1497.8 (888.2)	1205.9 (715.1)	919.3 (545.1)
FRAP (SSD)	0.0 (0.0)	375.3 (222.6)	651.9 (386.6)	924.5 (548.2)	-	-	-	-
Dirty FRAP (SSD) ¹	-	-	-	-	0.0 (0.0)	374.4 (222.0)	649.3 (385.1)	919.3 (545.1)
Sand1 (SSD)	1129.6 (669.9)				-	-	-	-
Sand2 (SSD)	-	-	-	-	1065.7 (632.0)			
Water	230.9 (136.9)							
AEA ²	1.15 (0.75)							
WRDA ²	4.5 (2.93)	4.3 (2.80)	4.25 (2.77)	4.25 (2.77)	4.4 (2.87)	4.4 (2.87)	4.25 (2.77)	4.2 (2.74)

¹ Dirty FRAP proportions are the same for the dirty and also washed and sieved dirty FRAP

² Listed as dosage of fluid ounces per 100 pounds cementitious (mL per 100 kg cementitious)

The compressive and split tensile strengths were evaluated using 4 by 8 inch (100 by 200 mm) cylindrical specimens. The compressive and split tensile strengths were evaluated following AASHTO T22 (2007) and AASHTO T198 (2009), respectively. The flexural strength was evaluated by third-point (4 point) loading on 6 by 6 by 21 inch (150 by 150 by 530 mm) prisms in accordance with AASHTO T97 (2003).

Results and Discussion

Washed FRAP The fresh properties of the concrete with FRAP can be found in Table 3. For similar chemical admixture dosages, it was found that the air content was relatively unaffected by increasing FRAP content. The unit weight decreased with increasing coarse FRAP replacement levels. Additionally, the slump typically increased with the higher FRAP contents, which can also be seen in Table 2 with the lower WRDA requirement for mixes with higher FRAP contents.

Table 3. Fresh Properties of Concrete Containing FRAP

FRAP Content	Air Content (%)	Slump, inch (mm)	Unit Weight, lb/ft ³ (kg/m ³)
0%	7.9%	2-1/4 (57)	143.2 (2294)
20%	7.4%	2-1/4 (57)	142.4 (2281)
35%	7.5%	4-1/2 (114)	141.0 (2259)
50%	7.0%	4-1/2 (114)	141.6 (2268)

The primary FRAP study was evaluated for compressive and split tensile strengths at 3, 7, 14, 28, and 90 days, as plotted in Figure 2 and Figure 3, respectively. Concrete flexural strength specimens were evaluated at 14 and 28 days (see Figure 5). For each testing age, the reported strength is the average of three test specimens.

With the exception of the results at 90 days, the introduction of FRAP coarse aggregate into the concrete resulted in a decrease in the compressive strength (Figure 2). The expected trend would be that the 50% FRAP mix would result in a lower compressive strength than the 35% FRAP mix. However, at times the 50% FRAP mix had a compressive strength nearly as high as the 20% FRAP mix (see 3 and 14 days). The behavior at 28 days is particularly intriguing, given that the mix with 20% FRAP had a lower compressive strength than that tested at 14 days. The coefficient of variation at 28 days was much greater than that for the 20% FRAP mix, which could explain the unexpected trend at this age. Bilodeau et al. (2011) found greater standard deviations at later ages for the compressive strength, although the split tensile standard deviation was not consistent with age. Kolas (1996) also found coefficients of variation that were inconsistent with age for the compression, split tension, and flexural strengths.

Several possible reasons for the relatively high compressive strengths found with multiple concrete mixes with FRAP may be due to the variable amount of asphalt adhered to the coarse aggregate particle and the agglomerated FRAP particles. The asphalt content by weight of FRAP was found to be 2.1%, which is much less than the typical 4-5% asphalt content for a coarse asphalt concrete material. The reduction in asphalt content is due in part to coarser particles being used and the washing process. As visually observed in Figure 1, there are numerous exposed faces on the aggregate particles which can enhance the aggregate-paste bond and elevate the strength of the concrete. Agglomerations of asphalt and finer aggregate particles forming a larger aggregate can produce a weak FRAP-paste interface as well as a lower modulus. In the primary FRAP source, approximately 14% by weight was found to be agglomerated particles. Overall, the trends in compressive strength are more variable than one would expect, which is due to the complex failure mechanisms with this mode of loading combined with the highly variable FRAP-paste interface.

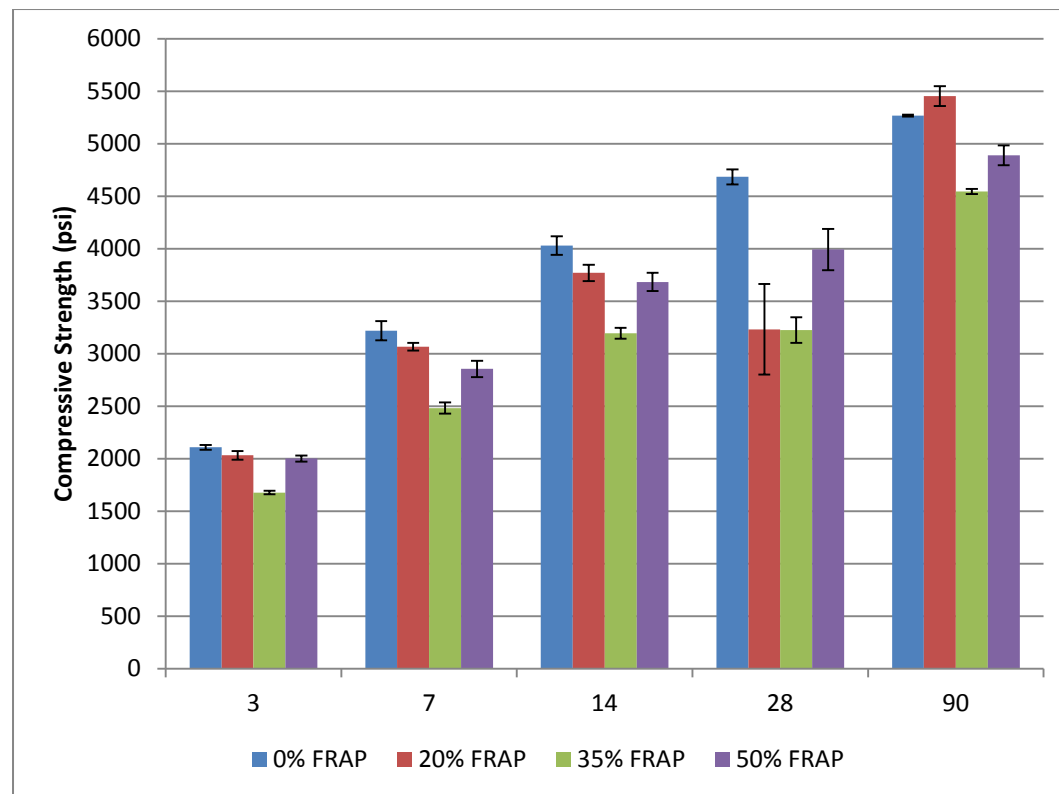


Figure 2. Compressive strength at 3, 7, 14, 28, and 90 days for the 0, 20, 35, and 50% FRAP mixes. Error bars indicate one standard deviation. Conversion: 1 psi = 6.9 kPa.

Figure 3 shows much clearer trends of decreasing split tensile strength with increasing contents of FRAP. Compared to the 0% FRAP control mix, the 50% FRAP mix had almost a 50% reduction in split tensile strength at 28 days. As seen in Figure 4 for the split tensile fracture surface, cracking propagated through some FRAP particles and went around other particles. Many of the fractured FRAP particles had either an exposed face or very thin asphalt coatings, which indicated a better bond with the cementitious matrix. The cracks that went around the coarse FRAP were typically agglomerated particles or FRAP particles with a thicker asphalt coating. This split tensile strength reduction with increasing FRAP content strongly suggests that the FRAP-paste bond is a major contributor to the decrease in observed strength.

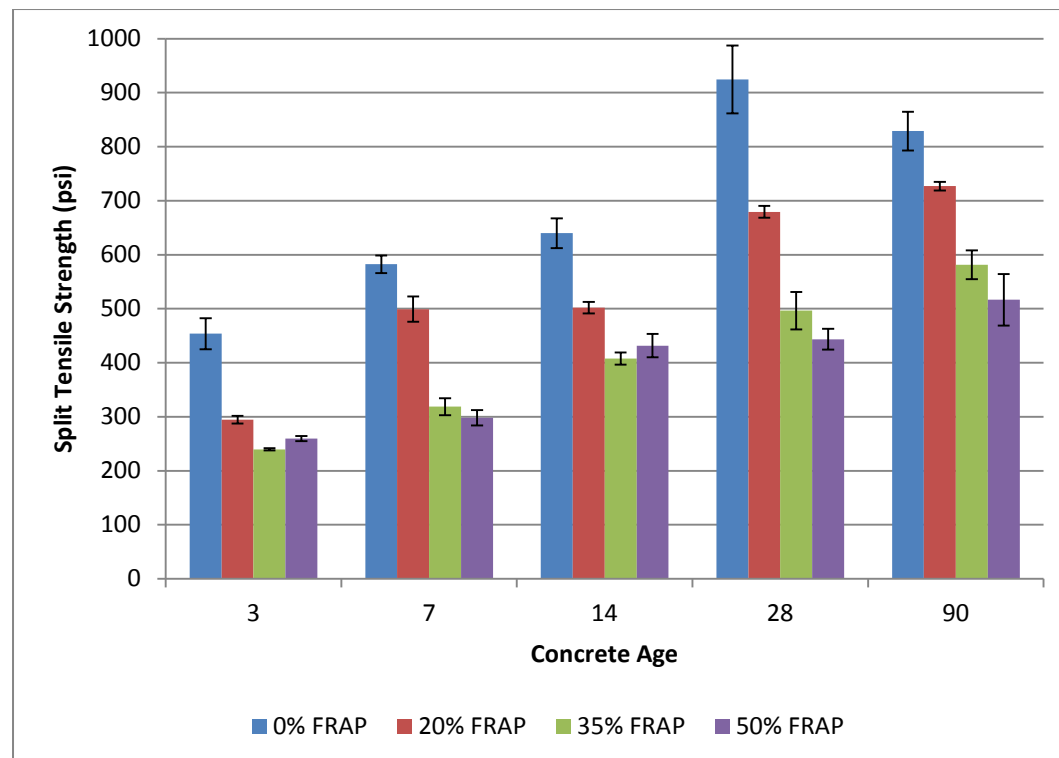


Figure 3. Split tensile strength at 3, 7, 14, 28, and 90 days for the 0, 20, 35, and 50% FRAP mixes. Error bars indicate one standard deviation. Conversion: 1 psi = 6.9 kPa.



Figure 4. Split tensile specimen with 50% FRAP mix at 28 days. The bluish-turquoise color is due to slag hydration.

Similar to the compressive and split tensile strengths, the flexural strength decreased with higher FRAP contents, as seen in Figure 5. At 14 days, there is a clear trend that the flexural strength decreases with increasing FRAP replacement. At 28 days, the range in flexural strength values increased from 0 to 50% FRAP

replacement, as the aggregate-paste bond improved for the virgin coarse aggregate mixture. The 50% FRAP mixture did not gain strength from 14 to 28 days, while the other FRAP mixtures experienced nominal increases in strength. Flexural strength values are typically 20 to 30% greater than the split tensile strength value. For this study, the FRAP concrete had an 8% higher flexural strength compared to split tensile for the 20% FRAP mix, a 57% difference in the mix with 35% FRAP, and a 30% difference in the 50% FRAP mix. For the control mix (0% FRAP), the flexural strength was 7% lower than the split tensile strength.

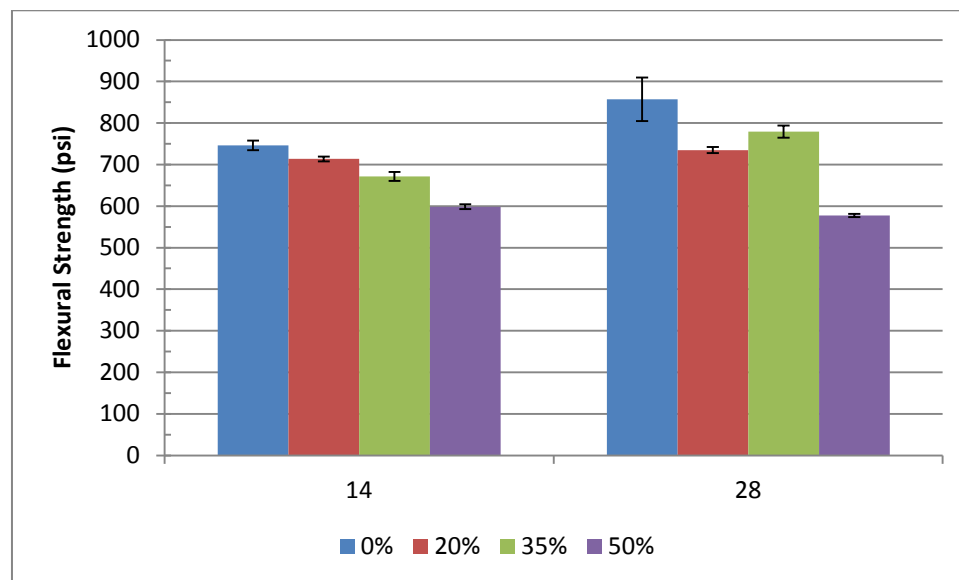


Figure 5. Flexural strength at 14 and 28 days for the 0, 20, 35, and 50% FRAP mixes. Error bars indicate one standard deviation. Conversion: 1 psi = 6.9 kPa.

The Tollway follows the Illinois Department of Transportation (IDOT) guidelines which requires minimum strengths of 3500 psi (24,000 kPa) compressive and 650 psi (4500 kPa) flexural (3-point, or center-point, loading) at 14 days for paving concrete (IDOT 2012). Overall, the compressive strength reductions at 14 days were 6%, 21%, and 9% for the FRAP contents of 20%, 35%, and 50%, respectively, and at 28 days, the reductions were 31%, 31%, and 15%, respectively. The flexural strength reductions at 14 days were 4%, 10%, and 20% for the FRAP contents of 20%, 35%, and 50%, respectively. Although the compressive strength results do not all pass the 14 day minimum specification (i.e. 35% FRAP), all replacement levels exceed 4500 psi at 90 days. Three-point (center-point) flexural strength is approximately 15% greater than the 4-point loading results (Ozyildirim and Carino 2006). Therefore, flexural strength criterion is met with 0, 20, and 35 percent FRAP replacements at 14 and 28 days. However with 50% FRAP replacement, the average flexural strength is too close to the minimum specification which means some specimens are not achieving the 650 psi minimum value. At 50% FRAP replacement, the thickness design of the concrete pavement would need to be adjusted for its reduced strength.

Dirty FRAP A secondary study was initiated to examine an independent finer graded FRAP source with a 1/2 inch (12.5 mm) maximum aggregate size under three different initial conditions: unprocessed dirty FRAP, washed dirty FRAP over a #4 (4.75 mm) sieve, and dry-sieved dirty FRAP to remove all particles passing the #4

(4.75 mm) sieve. The objective of this secondary study was to determine if the additional processing of dirty FRAP (i.e. washing or additional sieving) was necessary. Similar to the primary study, the dirty FRAP replacement levels were 0, 20, 35, and 50%.

No strong trends were seen in air content as the dirty FRAP content increased, as noted in Table 4. The slump increased slightly with the addition of the dirty and processed dirty FRAP, which is concluded by noting the reduction in the required WRDA for a given slump level as presented in Table 2. The unit weight trend was not as clear compared to the primary FRAP source.

In general, there were no discernable trends between the clean and dirty FRAP sources. The slumps were similar for the 0 and 20% FRAP replacements, but the slump was lower for the 35 and 50% dirty FRAP replacements compared to the primary source FRAP. As expected, the overall the unit weight was reduced in mixes with the dirty FRAP compared to the clean FRAP, since the dirty FRAP and second sand source had lower specific gravities than the clean FRAP.

Table 4. Fresh Properties of Concrete with Dirty FRAP

Dirty FRAP Mix	Air Content (%)	Slump, inch (mm)	Unit Weight, lb/ft³ (kg/m³)
0%	6.9%	2-3/4 (70)	138.2 (2214)
20% Dirty	6.2%	3 (76)	142.8 (2288)
35% Dirty	5.3%	2 (51)	145.0 (2323)
50% Dirty	7.2%	3-1/4 (83)	138.6 (2220)
20% Sieved	6.4%	2-1/4 (57)	144.0 (2307)
35% Sieved	7.2%	3 (76)	140.6 (2252)
50% Sieved	6.6%	2-1/2 (64)	141.2 (2262)
20% Washed	7.1%	3-1/4 (83)	142.2 (2278)
35% Washed	7.6%	3-1/2 (89)	139.8 (2240)
50% Washed	7.8%	3-1/4 (83)	138.4 (2217)

For the three initial conditions of the dirty FRAP (i.e. dirty FRAP, washed dirty FRAP, and sieved dirty FRAP), the compressive and split tensile strengths decreased with increasing dirty FRAP content, as seen in Figure 6, Figure 7, and Figure 8. The trends of a reduction in strength with increasing dirty FRAP content were consistent for all split tensile strengths and all dirty FRAP conditions; larger coefficients of variation were noted compared to those obtained when the primary FRAP source was used. Interestingly, for mixes with 20% and 35% FRAP, the strength was highest for the unprocessed dirty FRAP, then the sieved dirty FRAP, and finally the washed dirty FRAP. At 50% replacement, the dirty FRAP mix had the lowest strength, although the strengths of all of the dirty FRAP mixtures were within 10% of each other.

For the secondary FRAP source, the compressive and split tensile strength data suggested that the dirty FRAP (unprocessed) achieved the best or similar strength compared to the washed FRAP for replacement levels of 20 and 35%. One factor not closely controlled in this study was the combined gradation for the various mixtures. Hence gradation may have influenced the observations. In terms of specification requirements, all mixtures in the dirty FRAP study met the IDOT 3500 psi (24,000 kPa) compressive strength requirement at 14 days and would likely meet the flexural strength requirement if the split tensile strength is at least approximately 80% of the

flexural strength (see Figure 8). Lastly, this secondary FRAP source produced overall greater strengths for similar mixture proportions compared to the washed FRAP that was previously presented.

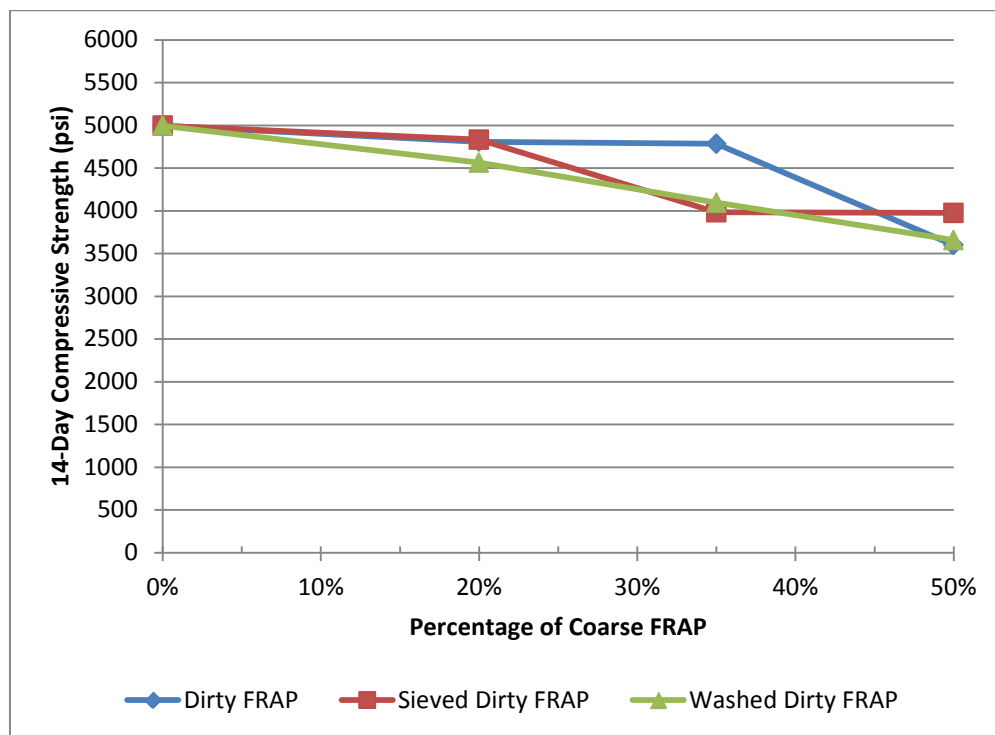


Figure 6. Compressive strength at 14 days for the 0, 20, 35, and 50% dirty FRAP, washed dirty FRAP, and sieved dirty FRAP mixes. Conversion: 1 psi = 6.9 kPa.

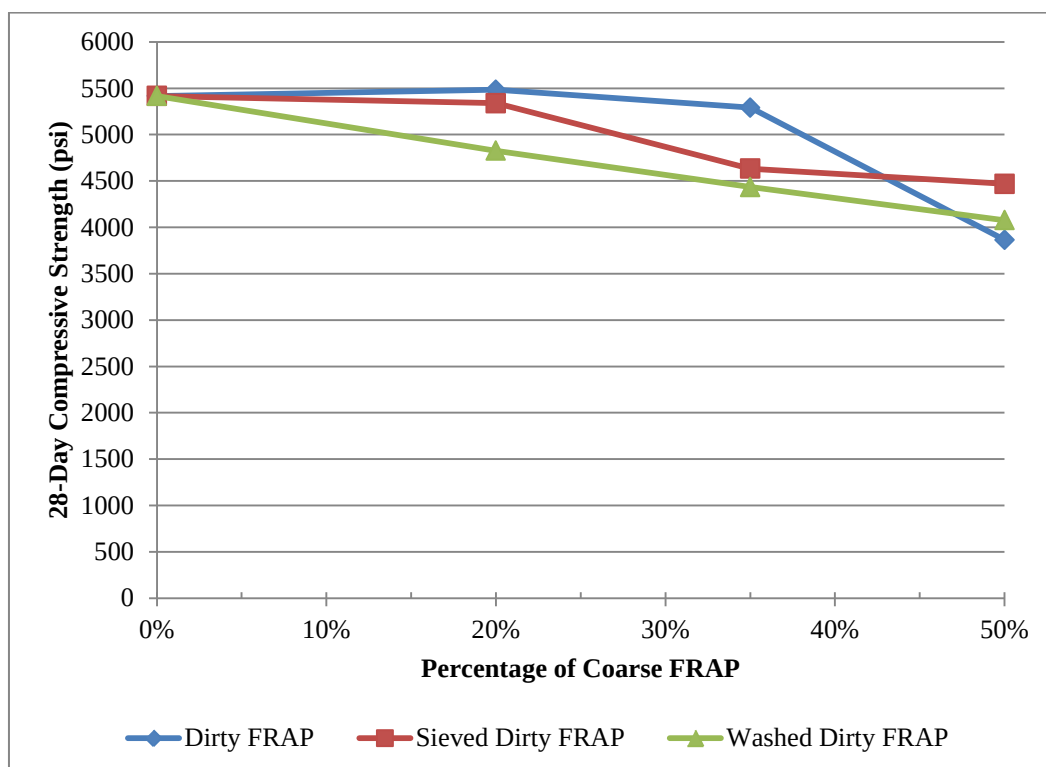


Figure 7. Compressive strength at 28 days for the 0, 20, 35, and 50% dirty FRAP, washed dirty FRAP, and sieved dirty FRAP mixes. Conversion: 1 psi = 6.9 kPa.

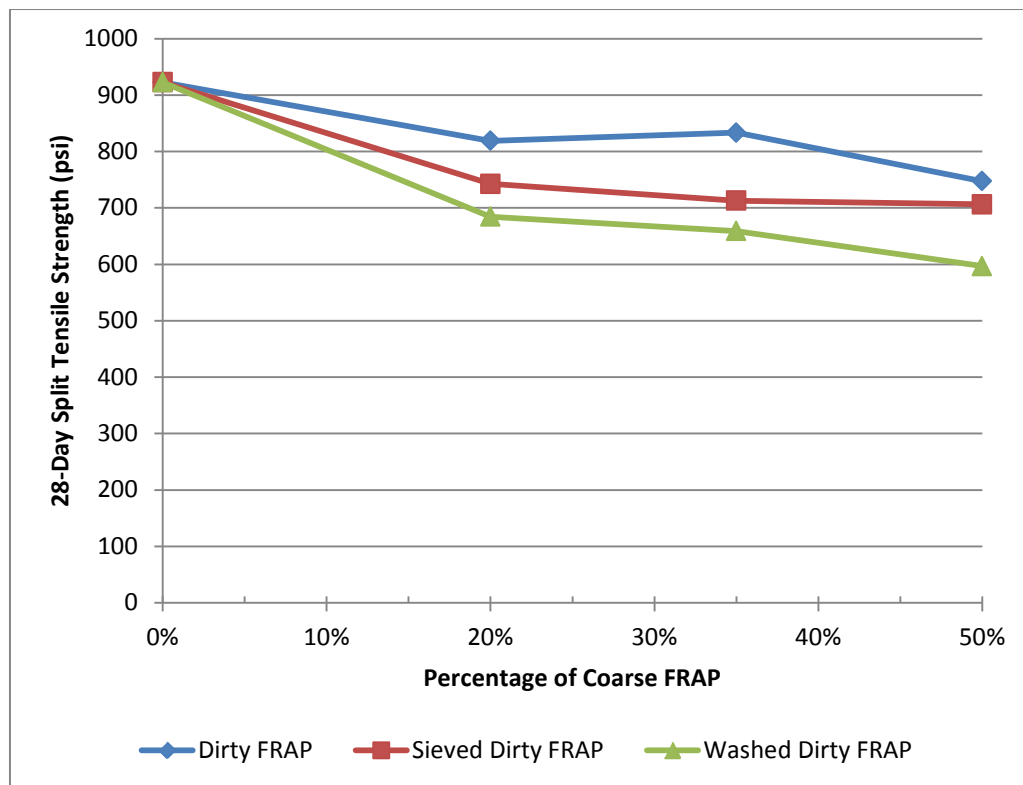


Figure 8. Split tensile strength at 28 days for the 0, 20, 35, and 50% dirty FRAP, washed dirty FRAP, and sieved dirty FRAP mixes. Conversion: 1 psi = 6.9 kPa.

Conclusions

With growing stockpiles of reclaimed asphalt pavement (RAP) from roadway rehabilitation projects, it is evident that feasible solutions must be developed to reduce the amount of this construction waste. This investigation aimed to reduce the amount of coarse fractionated reclaimed asphalt pavement (FRAP) disposal by incorporating it as a partial replacement (0, 20, 35, and 50%) of virgin coarse aggregate in a ternary blended concrete (65% cement, 25% slag, and 10% fly ash). This solution offers both environmental and economic benefits as it recycles roadway materials (RAP) and utilizes industrial by-product wastes (slag and fly ash) while still attempting to maintain the desired concrete properties.

Two RAP sources were considered in this research. The primary source study used a washed, clean FRAP to examine the effects on the fresh concrete properties and the compressive, split tensile, and flexural strengths. The secondary study assessed a dirty FRAP source and determined the effects of additional processing of the dirty FRAP by washing and additional sieving to remove the fine particles passing the #4 (4.75 mm) sieve.

The results of the testing verified that concrete with FRAP could potentially be used for rigid pavement applications provided that the mix is properly designed and validated against existing specifications. In fact, the two different FRAP sources demonstrated that different strength results would occur with similar mixture proportions. The first mixture containing 35% FRAP was shown to obtain sufficient strength for the roadway requirements in Illinois (compression and flexural strength) while and the secondary FRAP source could also meet the specifications at the 50% replacement level (compressive strength). Based on the dirty FRAP test data, it was concluded that additional processing, washing, or secondary screening did not improve the fresh and hardened concrete properties for this FRAP source.

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References

AASHTO Standard T97. (2003). "Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)." American Association of State Highway and Transportation Officials, Washington D.C.

AASHTO Standard T22. (2007). "Compressive Strength of Cylindrical Concrete Specimens." American Association of State Highway and Transportation Officials, Washington D.C.

AASHTO Standard T198. (2009). "Splitting Tensile Strength of Cylindrical Concrete Specimens." American Association of State Highway and Transportation Officials, Washington D.C.

ASTM C192. (2007). "Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory." American Society for Testing Materials International, West Conshohocken.

Al-Oraimi, S., Hassan, H. F., and Hago, A. (2009). "Recycling of Reclaimed Asphalt Pavement in Portland Cement Concrete." *J. Eng. Res.*, 6(1), 37-45.

Bilodeau, K., Sauzéat, C., Di Benedetto, H., Olard, F., and Bonneau, D. (2011). "Laboratory and In Situ Investigations of Steel Fiber Reinforced Compacted Concrete Containing Reclaimed Asphalt Pavement." *90th Annual Meeting of the Transportation Research Board*, Washington D.C.

Delwar, M., Fahmy, M., and Taha, R. (1997). "Use of Reclaimed Asphalt Pavement as an Aggregate in Portland Cement Concrete." *ACI Mater. J.*, 94(3), 251-256.

Dumitru, I., Smorchevsky, G., and Caprar, V. (1999). "Trends in the Utilisation of Recycled Materials and By-Products in the Concrete Industry in Australia." *Concrete 99: Our Concrete Environment*, Sydney, Australia, 289-301.

Hassan, K. E., Brooks, J. J., and Erdman, M. (2000). "The Use of Reclaimed Asphalt Pavement (RAP) Aggregates in Concrete." *Waste Materials in Construction*, Elsevier Science, Oxford, 121-128.

Hossiney, N., Wang, G., Tia, M., and Bergin, M. J. (2008). "Evaluation of Concrete Containing RAP for Use in Concrete Pavement." *87th Annual Meeting of the Transportation Research Board*, Washington D.C.

Hossiney, N., Tia, M., and Bergin, M. J. (2010). "Concrete Containing RAP for Use in Concrete Pavement." *International Conference on Sustainable Concrete Pavements*, Sacramento, California.

Huang, B., Shu, X., and Li, G. (2005). "Laboratory Investigation of Portland Cement Concrete Containing Recycled Asphalt Pavements." *Cement and Concrete Res.*, 35(10), 2008-2013.

Huang, B., Shu, X., and Burdette, E. G. (2006). "Mechanical Properties of Concrete Containing Recycled Asphalt Pavements." *Mag. Concrete Res.*, 58(5), 313-320.

IDOT. (2012). "Standard Specifications for Road and Bridge Construction." Illinois Department of Transportation, Springfield, Illinois.

Kolias, S. (1996). "Mechanical Properties of Cement-Treated Mixtures of Milled Bituminous Concrete and Crushed Aggregates." *Mater. Struct.*, 29, 411-417.

Mathias, V., Sedran, T., and de Larrard, F. (2004). "Recycling Reclaimed Asphalt Pavement in Concrete Roads." *International RILEM Conference on the Use of Recycled Materials in Buildings and Structures*, Barcelona, Spain.

Okafor, F. O. (2010) "Performance of Recycled Asphalt Pavement as Coarse Aggregate in Concrete." *Leonardo Electron. J. Pract. Technol.*, 17, 47-58.

Ozyildirim, C. and Carino, N. J. (2006). "Concrete Strength Testing." *Significance of Tests and Properties of Concrete and Concrete-Making Materials*, ASTM STP 169D, editors J. F. Lamond and J. H. Pielert, ASTM International, West Conshohocken, 125-140.

Sommer, H. (1994) "Recycling of Concrete for the Reconstruction of the Concrete Pavement of the Motorway Vienna-Salzburg." *7th International Concrete Roads Symposium*, Vienna, Austria.

Sommer, H. and Bohrn, J. (1998). "Beton mit Asphalt als Zuschlag (Concrete with Extra Asphalt)." Bundesministerium für wirtschaftliche Angelegenheiten (Federal Ministry of Economic Concerns), Schriftenreihe Straßenforschung (Roadway Research Project Series), 476. (in German)

Vavrik, W. R., Carpenter, S. H., Gillen, S., Behnke, J., and Garrott, F. (2008). *Evaluation of Field-Produced Hot Mix Asphalt (HMA) Mixtures with Fractionated Recycled Asphalt Pavement (RAP)*. Report No. ICT-08-030. Applied Research Associates, Illinois State Toll Highway Authority, Downers Grove, Illinois.