Effect of Warm Mix Asphalt (WMA) Low Mixing and Compaction Temperatures on Recycled Asphalt Pavement (RAP) Binder Replacement

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16. Abstract

The use of Warm Mix Asphalt (WMA) technologies in asphalt concrete production allows for economic and environmental benefits. Incorporating high Reclaimed Asphalt Pavement (RAP) contents in mixes at WMA temperatures poses a challenge in the ability to attain the quality of produced pavements. It is unknown if WMA production conditions influence the full integration of RAP in the mixes, thus its overall performance. This study examines the effect of six factors including mixing/compaction temperatures, RAP content and source, WMA type, binder grade, and conditioning duration on mixture compaction, and cracking resistance. The results show that at 15% RAP WMA mixes can meet volumetric limits at the warm production temperature level. However, at 30% RAP, hot production temperature is required to achieve the same level of compaction. Binder grade, conditioning duration, and WMA additive types considered in this study showed minimal influence on the compaction results. Cracking resistance of the mixes is shown to be overwhelmingly influenced by the RAP content. The study results show that meeting the mix design volumetric requirements did not necessary translate into improved cracking performance. The interaction between the WMA and higher RAP level (30%) is complex as it is dependent on RAP source, production temperature, and binder grade.

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1 INTRODUCTION

In the past decade, there has been a great emphasis on the incorporation of Reclaimed Asphalt Pavement (RAP) and Reclaimed Asphalt Shingles (RAS) materials in asphalt concrete mixes. The move toward the use of more recycled pavement materials, and the reduction of the waste that is discarded in land fill is accompanied by a shift in the industry toward the use of Warm Mix Asphalt (WMA) technologies. WMA aims to decrease the negative environmental impact of asphalt concrete production, as well as to reduce the cost of this process.

Practical issues arise when the use of WMA technologies is combined with the incorporation of high RAP contents into asphalt concrete mixes. One of the most crucial aspects is the effect of the reduction in the production temperatures on the binder blending efficiency, constructability, and performance of high-RAP WMA mixes. Another aspect is the amount of RAP that can be incorporated in WMA mixes without adversely affecting the properties of the mixes.

The aim of this research effort is to improve the understanding of the interaction of WMA additives and high RAP content mixes. The available literature was examined to identify the factors that play a significant role in affecting the RAP binder replacement in high-RAP WMA mixes. Based on the factors that were identified in the literature review process of this project, a two-phase experimental program was developed to investigate the effect of these factors on the production quality of high-RAP WMA mixes.

<u>Phase I</u> of the study, focused on the sensitivity of the mixes to the mixing and compaction temperatures, as well as the sensitivity to the RAP binder replacement level. <u>Phase II</u> of the program covered the cracking resistance of selected mixes based on the results obtained from Phase I of the study. The selection process was made by first studying the effect of six (6) factors, which were identified in the literature review process, on the volumetric properties and workability of the high-RAP WMA. This was followed by identifying the factors that showed statistically significant influence on the studied mixes, and incorporating these factors in the experimental program for the cracking performance evaluation.

The evaluation of the cracking performance of the mixes was examined using the Semi-Circular Bend (SCB) test. The SCB testing was conducted at intermediate temperatures to provide knowledge on the fracture resistance of the mixes at service temperatures.

2 LITERATURE REVIEW

2.1 Warm Mix Asphalt and Recycled Materials

Warm Mix Asphalt (WMA) mixes are becoming more broadly used with the movement toward an environmentally friendly and sustainable pavement industry. After emerging from Europe in the 1990s, WMA was introduced in the United States (US) in the early 2000s, and since then, it started to replace conventional Hot Mix Asphalt (HMA) mixes. By 2015, WMA mixes comprised about one third of the produced asphalt mixtures (Hansen et al. 2015). WMA technology is supported by the Everyday Counts (EDC) initiative by the Federal Highway Administration (FHWA). Figure 1 is adopted from a 2015 published study by Christies. The plot presents the significant jump in WMA utilization between 2010 and 2014. Utilization increased from about 3% to about 40% in this four year window.

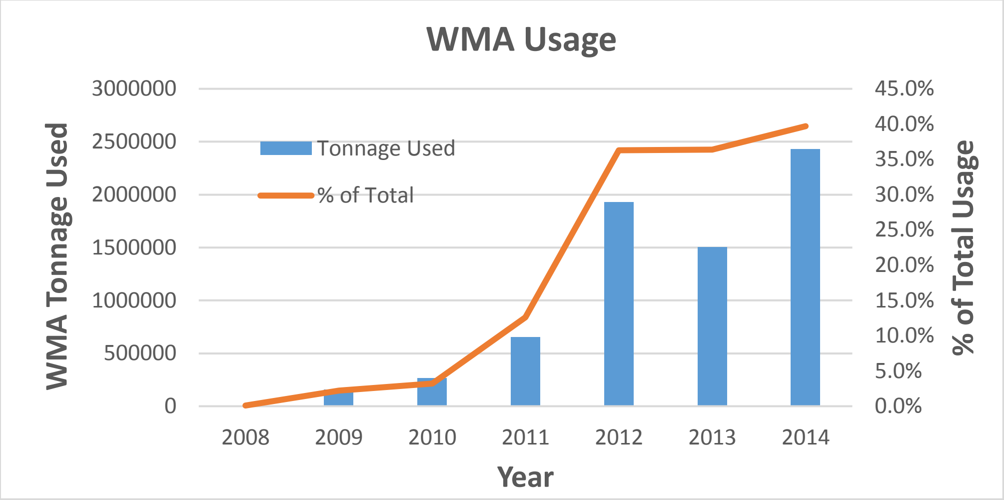


Figure 1 - WMA Usage between years 2008-2014 (Christie 2015)

This jump in WMA utilization is attributed to its desirable benefits. One such benefit is the lowered production temperature, which according to the FHWA, ranges from 30°F to 120°F less than typical HMA. This translates to reduced energy needed to heat the material leading to reduced cost. For example, the reduction in expenses of burner fuels alone is about 20-35 %. This also allows for opening roads to traffic after a shorter length of time (Button et al. 2007, D'Angelo et al. 2008, Zaumanis 2010, Capitão et al. 2012). WMAs can also increase the haulage distances and extend the paving season (Hurley & Prowell 2005, Kristjansdottir 2006, Martin 2014). It allows for easier compaction at lower temperatures as well as the potentially slower rate of aging of the binder (Bennert 2015).

Environmentally, WMA is reported to lower emission of greenhouse gases as well as being less of a health hazard for workers in the asphalt concrete industry (Lange et al. 2002, Kuennen 2004, D'Angelo et al. 2008, and Kim et al. 2012). Reductions of approximately (30-40)% in CO_2 emission, 35% in SO_2, 50% in VOC, (10-30)% in CO, (60-70)% in NO_x, and (20-25)% in dust emissions were reported in some studies as typical expected reductions percentages (Prowell 2007) (D'Angelo et al. 2008).

Despite some of the beneficial aspects of WMA technologies, the literature recognizes a few potential disadvantages. These disadvantages include: the possibility of an increase in the total cost of using WMA due to the use of additives, as well as the cost of equipment and plant changes that are necessary for some of these technologies (Button 2007, Zaumanis 2010). Also, there are concerns with potential moisture damage in WMA due to a reduced mixing temperature which may not allow all the moisture to evaporate (Capitão et al. 2012). In addition, with the current industry trend in encouraging increase Reclaimed Asphalt Pavement (RAP) content in asphalt pavements in general, it is unclear how WMA technologies would interact with high RAP content mixes. The lowered mixing and compaction temperatures may not provide enough energy to have the RAP binder contribute to the overall binder within the mixture.

The use of reclaimed asphalt pavement has also been on a constant rise for decades. Because of constant milling and resurfacing of old roads, large amounts of RAP are being produced. According to FHWA, about 100 million tons of reclaimed asphalt pavement is produced each year as a result of resurfacing practices (APA 2001). The rise in asphalt binder costs along with less good quality aggregate being readily available has played a major role in increasing the use of RAP in HMA mixes (Copeland et al. 2010, Hossain et al. 2012). Figure 2 illustrates the trend in RAP utilization over the decade from 2004 to 2014. RAP moved from being utilized in about 30% of HMA produced to over 90%.

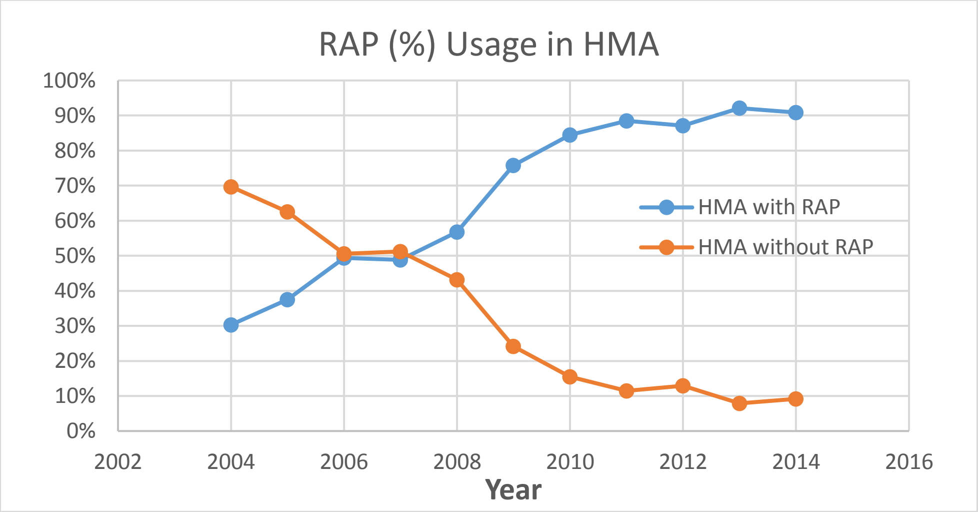


Figure 2 - Increase in the use of reclaimed asphalt pavement in HMA mixes (Christie 2015).

Incorporation of the RAP into new mixes helps reduce the amount of waste of the material being sent to landfills and the harm to the environment in the process. RAP is expected to replace some of the more expensive virgin materials, and lower life-cycle costs (Huang et al. 2007, Chiu et al. 2008, and Lee et al. 2010). For example, the incorporation of RAP and Recycled Asphalt Shingles (RAS) together allowed for a $2.8 billion savings in costs of virgin materials (Hansen et al. 2015). Nevertheless, incorporation of high RAP amounts in conventional HMAs requires heating the material to significantly high temperatures which in turn leads to further aging of the already aged binder (Dinis-Almeida et al. 2016). This high heat also requires more energy consumption, which translates to higher costs and higher emissions (Dinis-Almeida et al. 2016).

In 2008 D'Angelo et al. presented two (2) possible benefits, which are found in the literature, for combining WMA technologies with RAP. The first is reduced resistance to compaction, and the second is potentially lower levels of early stage aging due to gentle production temperatures. These benefits are expected to counterbalance the effect of the aged RAP binder (D'Angelo et al. 2008). As mentioned earlier, as the RAP content increases, more energy is required for the RAP binder to participate in the overall binder content. The issue of successful binder replacement at the lowered WMA mixing and compaction temperatures needs to be addressed. Also, there is a need for establishing mix-design guidelines that take into consideration the large variety of WMA technologies and the performance of resulting mixes when combining these technologies with high-RAP percentages to produce asphalt concrete.

Many studies have looked into the issue of RAP binder blending with virgin binder in conventional mixes (Huang et al. 2005, Shirodkar et al. 2011, Nahar et al. 2013, Zhao et al. 2013, and Bowers et al. 2014). Also several studies characterized the mobilization and blending of aged binder in the context of WMA incorporating RAP and RAS (Bonaquist 2011, Gaitan 2012, Zhao et al. 2015, Xiao et al. 2016 and others). A review of these studies is presented in "RAP Binder Replacement in WMA Mixes" section.

2.2 Warm Mix Asphalt Technologies

WMA technologies are used to achieve a similar coating of aggregates, as in conventional HMA mixes but at a lower production temperature, and to produce pavements that perform better or similar to conventional HMA pavements (Capitão 2012). WMA mixes are reported to be produced at approximately 30°F to 75°F lower than conventional HMAs (Hurley & Prowell 2005, Copeland et al. 2010, Martin 2014).

There are different WMA technologies currently being utilized. In general, WMA technologies can be categorized into three (3) main types based on the mechanism with which coating of the aggregates is made possible (European Asphalt Pavement Association (EAPA) 2010, Prowell et al. 2011, and Kim et al. 2012):

2.2.1 Foaming technology

In this type of WMA technology use, a small amount of water is added to the mix. The water vaporizes and causes a temporary expansion of the asphalt and a reduction in its viscosity. This facilitates coating of the aggregates at lower temperatures (EAPA 2010). Common foaming technologies are Advera®, Aspha-min®, Low Energy Asphalt (LEA), Astec Double Barrel Green™. The foaming technology comprises more than 84% of the total WMA mix industry, while the other additives collectively form the remaining 16% (Hansen et al. 2015).

2.2.2 Chemical additives

Chemical additives that work as surfactants that reduce the friction at the interface between the binder and the aggregate, which allows for a lower mixing temperature to be used (Capitão 2012). Common chemical additives are Evotherm™ and Rediset®. Evotherm was used as an emulsion (Evotherm ET) that contained 70% binder. Another generation (Evotherm DAT) which contained less water, was introduced as a solution to be added directly to the binder line at the plant. Later, a third generation (Evotherm 3G) product was developed in which no water is used (Bonaquist 2011).

2.2.3 Organic additives

These additives are either waxes or fatty amides, reduce the binder viscosity above the melting point of the wax being used (EAPA 2010). In addition to reducing the required mixing temperature, the wax increases the stiffness of the binder when cooled down to room temperature. This takes place due to the crystallization of the wax that forms a lattice structure at the microscopic level (Butz et al. 2001, Capitão 2012). Common waxes are Sasobit^{TM} and Asphaltan B®. Sasobit^{TM} is a crystalline hydrocarbon that is produced using Fischer-Tropsch (FT) process in the gasification of coal (Abraham et al. 2002). Sasol Wax, which produces Sasobit, recommends using the additive at a rate of 0.8%-3% of the binder weight (Hurley & Prowell 2005). Table 1 provides a list of common warm mix asphalt technologies (Bonaquist 2011):

Table 1 - List of common WMA technologies (Bonaquist 2011)

Name	Process/Additive	Company	Website
Accu-Shear Dual Warm Mix Additive System	Foaming system	Stansteel	http://www.stansteel.com/sip.html
Advera	Zeolite	PQ Corporation	http://www.pqcorp.com/products/AdveraWMA.asp
AQUABLACK	Foaming system	Maxam Equipment Company, Inc.	http://maxamequipment.com/AQUABlackWMA.htm
Asphaltan –B	Montan wax	Romonta	http://www.romonta.de/ie4/english/romonta/i_wachse.htm
Double Barrel Green	Foaming system	Astec, Inc.	http://www.astecinc.com/
Evotherm	-	Ingevity	http://www.ingevity.com/markets/asphalt-and-paving/evotherm/
Licomont BS-100	Fatty acid derivative	Clariant	http://www.clariant.com/en/Solutions/Products/2014/03/18/16/33/Licomont-BS-100-granules
Low Emission Asphalt	Sequential coating using wet fine aggregate and unspecified additive	Suit-Kote	http://www.suit-kote.com/low-emission-asphalt-lea/
Meeker Warm Mix Asphalt System	Foaming system	Meeker Equipment	http://www.meekerequipment.com/new_warmmixad1.html
Rediset WMX	Unspecified additive	Akzo Nobel	https://sc.akzonobel.com/en/asphalt/Pages/product-detail.aspx?prodID=10451
Sasobit	Fischer Tropsch wax	Sasobit	http://www.sasobit.com/
THioPAVE	Sulfur plus compaction aid	Shell	www.shell.com/content/dam/shell/static/sulphur/downloads/thiopave-general.pdf

Name	**Process/Additive**	**Company**	**Website**
TLA-X	Trinidad Lake Asphalt plus modifiers	Lake Asphalt of Trinidad and Tobago	http://www.trinidadlakeasphalt.com/home/products/tla-x-warm-mixtechnology.Html
Ultrafoam GX	Foaming system	Gencor Industries, Inc.	http://gencorgreenmachine.com
WAM Foam	Soft binder followed by hard foamed binder	Kolo Veidekke, Shell Bitumen	www.shell.com/content/dam/shell/static/bitumen/.../shell-wamfoam-brochure.pdf

2.3 Mixing and Compaction Temperatures

WMA technologies are recognized for several advantageous qualities as mentioned earlier. Perhaps the most appealing is the lowered mixing and compaction temperatures. The goal is to produce pavements that are as durable as or better than HMA pavements while consuming less energy. To this end, it is vital that the effect of the lowered mixing and compaction temperatures in the production of WMA mixes, specifically with the use of high percentages of RAP, is studied thoroughly. The concern regarding the lowered production temperatures is related to several aspects of pavement construction and performance during service life. Workability, compactability mixes as well as blending efficiency, moisture susceptibility and rutting resistance of high RAP-WMA are among the key issues affected by the reduced production temperatures (Bonaquist 2011, Bennert et al. 2011, Jamshidi et al. 2013, and Zhao et al. 2015).

2.3.1 Workability and Compactability

A good level of workability is important for any asphalt mix to ensure adequate construction of the pavement. Due to the temperature dependency of asphalt binder, workability of an asphalt concrete mix is directly affected by temperatures at which the mixture is being prepared and handled. When using conventional HMA mixes, the suitable workability level is achieved by selecting the mixing and compaction temperatures based on the temperature at which the viscosity of the binder is suitable to accomplish adequate coating of the aggregate particles and lubrication for compaction of the mixture. This temperature is expected to be raised in mixes that incorporate RAP materials if the effective binder grade is increased because of the blending of aged and stiffened RAP asphalt binder with added virgin binder. In WMA mixes these elevated temperature are not reached. Instead, additives are mixed with the binder to assist in temporarily softening the binder so that adequate mixing and compaction can be achieved at lowered temperatures. Good workability is thus possible to be attained with the use of these alternative technologies in a virgin WMA mix. However, the question is raised about the effectiveness of these additives in case high amount of RAP is incorporated into the mix. This is because the lowered Warm Mix temperatures may not be enough to provide the needed heat energy to blend the RAP binder with virgin binder, thus RAP could act as black rock. This scenario means that the total effective binder in the mix will be reduced hampering constructability of the pavement and debilitating its overall mechanical stability and durability.

Several studies in the literature were conducted on the compactability of high RAP-WMA mix , however, the combined stiffening effect of the RAP binder along with the softening effect of the WMA additives are still not well understood (Reyes et al. 2009, Solaimanian et al. 2011, Bonaquist et al. 2011, Oliveira et al. 2012, Buss et al. 2015). Furthermore, the large variety of WMA technologies and the various mechanisms by which each type influences the compatibility of the RAP binder and virgin binders treated with warm mix technology are not fully studied in the literature, let alone at high RAP contents.

Solaimanian et al. in 2011 reported that for 15% and 35 % of RAP, WMA mixes showed a variation of +/- 0.5 in air void in comparison with similar HMA mixes, where the air voids always showed an increase when comparing Evotherm^{TM} mixes with the corresponding HMA mixes. On the other hand, Sasobit^{TM} and Foaming mixes showed a decrease in air voids with higher RAP percentages in the mixes. Table 2 shows the air void contents reported by Solaimanian et al at different RAP percentages. When comparing the virgin mixes with the 35% RAP mixes, it can be seen that incorporation of the RAP reduced the air content of all mixes. Also, at 35% RAP content, the RAP-Evotherm mix has the highest air content in the reported mix, while the RAP-Sasobit and RAP-Foaming air contents imply better compactability in comparison with the RAP-HMA.

Table 2 - Air void content at various RAP contents (adapted from Solaimanian et al 2011)

	0% RAP	**35% RAP**
	5.4% Asphalt Content	
Technology	**Air Voids %**	**Air Voids %**
HMA	5.6	4.1
Evotherm^{TM}	5.6	4.6
Sasobit^{TM}	5.4	3.5
Foaming	5.8	3.7

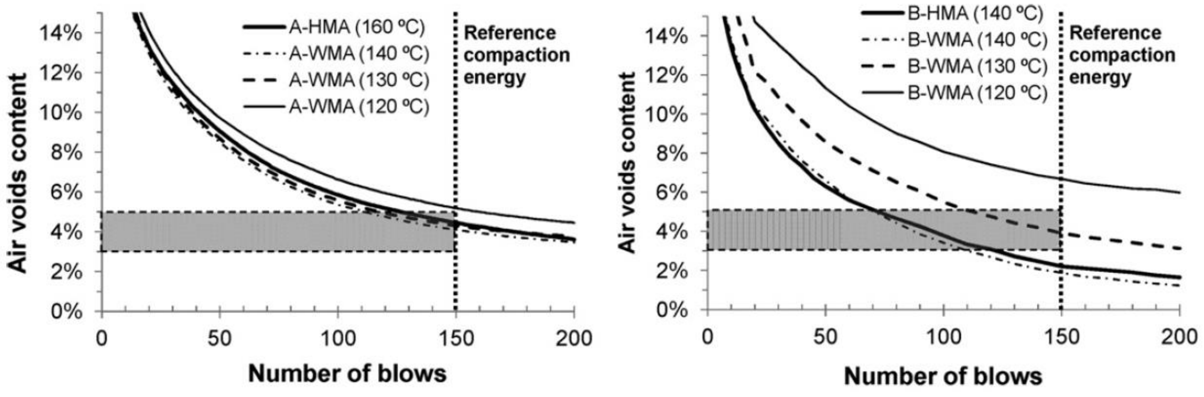
The results shown in Table 2 are counterintuitive. The authors did not provide an explanation to this observation of reduced air content with increased RAP content. While the majority of the studies reviewed showed an opposite trend, Reyes et al. in 2009 reported a similar trend in field study based filed compaction results that are discussed later in this this section.

In another 2011 study by Goh et al., the compactability of laboratory prepared hot mixed and warm mixed (-20^{o}C) porous asphalt mixtures was investigated with regards to the effect of 15% RAP added to the mixes. The WMA additive used in this study was Advera. The researchers reported that the average air voids of the WMA mix was higher than that of the HMA mix for both the virgin mixes (+0.74%) as well as the 15% RAP mixes (+0.4%). However, the authors also reported that the compaction energy for the WMA porous mixes both with RAP and without RAP were lower than the compaction energy for the corresponding HMA mixes.

NCHRP Report 691 included a comparative study between HMA and WMA (Advera & Sasobit) mixes on workability at different temperatures. The researchers used multiple methods to measure the workability including the UMass Workability Device, Gyratory Shear Stress, Nynäs Workability Device, and University of New Hampshire Workability Device. It was concluded that the differences in workability become significant at much lower temperatures than the typical WMA production temperatures. The authors also explored the use of the number of gyrations to achieve 8% air voids (at the compaction temperature and at a temperature 30°C below) as an indicator for the workability and compactability of WMA mixes. The results indicated that the difference between WMA and HMA mixes containing 25% RAP were small in terms of the numbers of gyrations to achieve the 8% air voids. However, the compactability of the 25% RAP-WMA mixes was significantly reduced when the compaction temperature was reduced 30°C, as depicted by the differences (WMA - HMA) in the percent increase in gyrations to achieve 8% air voids.

Mogawer et al. 2012 reported that the use of a wax-based WMA additive in mixes containing 40% RAP had minimal effect on the workability of the mixes. This was observed in both a mixtures containing polymer modified binder as well as a mixture containing unmodified binder.

Oliveira et al. in 2012 studied the effect of production temperatures on a high RAP-WMA mix containing 50% RAP and a small percentage of a surfactant WMA additive called CECABASE®. The authors investigated the compactability of virgin WMA mixes at different temperatures, and compared them with that of the RAP-WMA mixes. Results from the study indicated that in the absence of RAP, the variability in the air void is low across different temperatures, while in RAP containing WMA mixes, a large difference in the air voids was observed across the different production temperatures. Figure 3 shows a side by side comparison of the densification curves for virgin HMA and WMA (Figure 3a) and the same mixes with 50% RAP (Figure 3b).



(a) (b)

Figure 3 - Air void content at different mixing temperatures for (a) virgin WMA and HMA & (b) 50% RAP-WMA and 50% HMA mixes; (*adopted from* Oliveira et al. 2012).

As shown in the above figure, virgin WMA mixes prepared at 140°C & 130°C (compacted with 150 blows in the Marshall method) had almost equal air void percentage of about 4% as in the case of control HMA mix prepared at 160°C. However, in the case of 50% RAP-WMA mixes, the air void varied from approximately 2% for 140°C (same as RAP-HMA at 160°C) to 4% for 130°C, and about 6.8% for 120°C.

Several field studies also examined the compactability of RAP incorporating WMA mixes. Reyes et al. in 2009 reported on four (4) WMA mixes of different RAP contents (0%, 15% RAP, 15% RAP+ 5% RAS, and 50% RAP) after two (2) years of construction in western Canada. All mixes were produced with the use of Astec Double-Barrel Green foaming technology at 130-135°C. Average air void level in cored samples was 7.60, 6.63, 5.87, 7.33 for the mixes with 0% RAP, 15% RAP, 15% RAP + 5% RAS, and 50% RAP, respectively. The authors hypothesize that at the lower contents of the recycled materials, the foaming's softening effect is more palpable, while with the 50% RAP mix, the stiffening effect of the RAP overshadows the foaming influence. The same trend was reported in 2009 by Reyes et al. in regards to Tensile Strength Ratio (TSR) levels, were mixes with 0% RAP, 15% RAP, 15% RAP + 5% RAS, and 50% RAP registered TSR levels of 69.9, 84.2, 86.4, and 81.7 respectively.

Buss et al. in 2015 compared the densities of HMA and WMA cores incorporating different additive types with RAP contents of (5%-20%) after two (2) years of construction. The team reported that the RAP-WMA mixes had lower air voids for all projects, with the foamed WMA giving the largest difference of 1.8%. The differences were considered small for all the projects which suggest that the RAP-WMA mixes are not different from the RAP-HMA mixes in terms of compaction. Excluded from this was the foamed RAP-WMA that showed a considerably improved compaction.

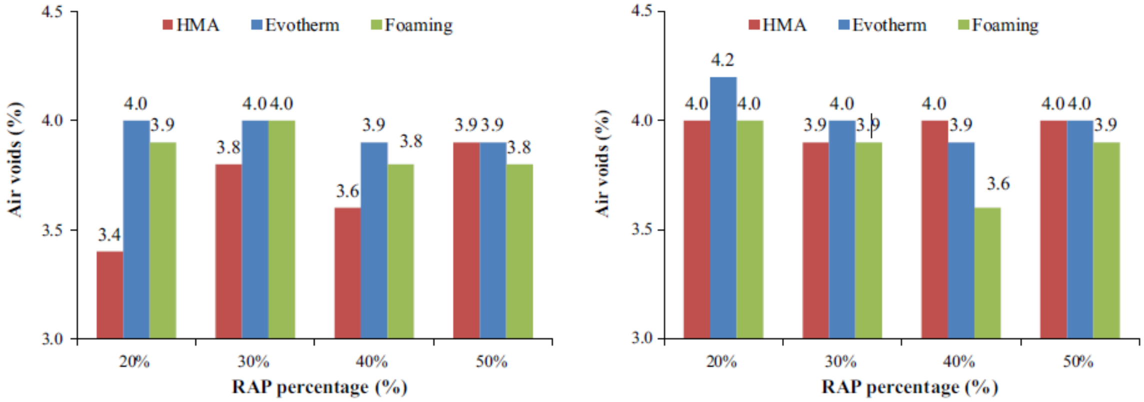
As demonstrated above, especially for high RAP content research studies show mixed results and evidence on the interaction between RAP and WMA. Recognizing the potential sources of these mixed results, it is important to identify these sources as findings of the literature search of this report. Type of WMA technology and dosage, mixing temperature and duration, RAP content, asphalt binder content, and mix design are among the potential factors influencing the mixed results reported in the literature.

2.3.2 Warm Mix Asphalt Technologies as Compaction Aid

WMA additives can be used at the same production temperatures as conventional HMA mixes. In such cases, it is presumed that they can serve as a lubricant that facilitates the compaction process of a HMA mix. This is specifically useful in high RAP mixes where the proper mixing of the materials would require a higher temperature to be maintained in the mixing and compaction processes, due to the stiffer nature of the RAP binder. In such instances, WMA additives can serve as a compaction facilitator without the need for further elevation of the temperature.

Tao et al. 2009 compared the bulk specific gravity (BSG) of a 100% RAP mix against that of a 100% RAP mix plus (1.5%, 2.0%, and 5.0%) Sasobit, as well as a 100% RAP mix plus (0.3%, 0.5%, and 0.7%) Advera zeolite. All mixes were prepared at 125°C. The authors reported a higher BSG value for the 1.5% Sasobit mix in comparison with the mix not containing any WMA additive. Furthermore, increase percentage of Sasobit further increase the achieved BSG, which is a sign of a better compaction level. The 0.3% Advera mix also resulted in a higher BSG, however the higher percentages had an adverse effect due to a possibly extensive expansion of the binder. The authors also measured the workability of the mixes using a torque tester. The workability of the mixes immediately after mixing (110°C) showed that both the RAP-Advera mix and the RAP-Sasobit mix had higher workability than the mix with no WMA additives. However, measurements of the workability after 1 hour (80°C), showed that both WMA mixes exhibited lower workability than the mix with no WMA additives (Tao et al. 2009).

Xiao et al. 2016 tested Evotherm and foamed WMA mixes at 20%, 30%, 40%, and 50% RAP additions. The authors used multiple binder, aggregate and RAP sources. The results from their work showed that for a given RAP content, compaction of laboratory samples vary depending on the asphalt binder source. The results of Xiao et al. 2016 are similar to those of Solaimanian et al. 2011 in that the air void was ±0.5% of that of the corresponding HMA mixes for almost all cases. Further, mixes with Evotherm were also reported to show higher air voids in the majority of the mixes. The Voids in Mineral Aggregates (VMA) of the mixes was also observed to be higher in the WMA mixes when compared with the HMA's, while the RAP content had an inverse relation with the VMA values.



(a) (b)

Figure 4 - Air voids in WMA and HMA mixes for different RAP contents. (a) Binder I (b) Binder II; (adopted from Xiao et al. 2016).

The results reported by Xiao et al. in 2016 and presented in Figure 4 clearly present the complexity of handling WMA mixes with high RAP content. The results show that changing the binder source can change the effectiveness of the WMA technology used. For example for Binder I, HMA samples are easier to compact at 40% RAP compared to all WMA samples. Binder II shows the exact opposite performance. On the other hand, at 50% RAP the difference between mixes and technologies disappear. This could be due to the fact that the RAP binder start to dominate the system.

2.3.3 *Reclaimed Asphalt Pavement Binder Replacement in Warm Mix Asphalt Mixes*

Several studies were conducted to investigate the blending of RAP binder in HMA mixes. While most agencies assume a 100% blending to occur in RAP containing HMA mixes (Johnson et al.

2010, Shirodkar et al. 2011, Zaumanis & Mallick et al. 2015), it is a subject of research and validation when it comes to WMA. The reason for this is there is not a broad literature on the long term performance of high RAP-WMA mixes, given that the technology is relatively new in the US. The mobilization of the RAP binder and its contribution to the total effective binder available in the mix is directly dependent on the mixing and compaction temperatures. It is hypothesized that during the mixing stage in conventional HMA mixes, the virgin binder coats the RAP binder surrounding the aggregate particles. While in the conditioning period, the two binders are expected to further blend and diffuse at the elevated temperatures. In high RAP-WMA mixes, however, the lower tempertures may adversly affect the diffusion of the RAP binder and its intermingling with the virgin binder (Jamshidi et al. 2013, Zhao et al. 2015). A limited number of studies addressed the issue of RAP binder blending with virgin binder in WMA mixes.

NCHRP Report-691 (Bonaquist et al. 2011) also included a RAP study where the blending of RAP-WMA mixes was evaluated by comparing the “measured” dynamic modulus of mixture samples that were short-term aged at different temperatures for durations of (0.5, 1, and 2 hours) with the “estimated” dynamic modulus from the binder recovered from these samples. Higher ratios of measured/estimated modulus indicated a better blending of the RAP binder with the WMA binder, with a ratio of 1 representing full blending (Bonaquist 2011). The RAP content used in the study was 25%. Figure 5 shows results reported by the author, where the ratios for (control, Advera, Evotherm, and Sasobit) mixes ranged between 0.35-0.55 for 0.5 hour and 1 hour aging durations at the different compaction temperature. However, increasing the duration to two (2) hours raised the ratio to approximately 1.0 for all mixes, excluding the Evotherm which remained low. Also higher compaction temperatures resulted in a distinguishable increase in the ratio of the measured to estimated moduli for two (2) hours of aging.

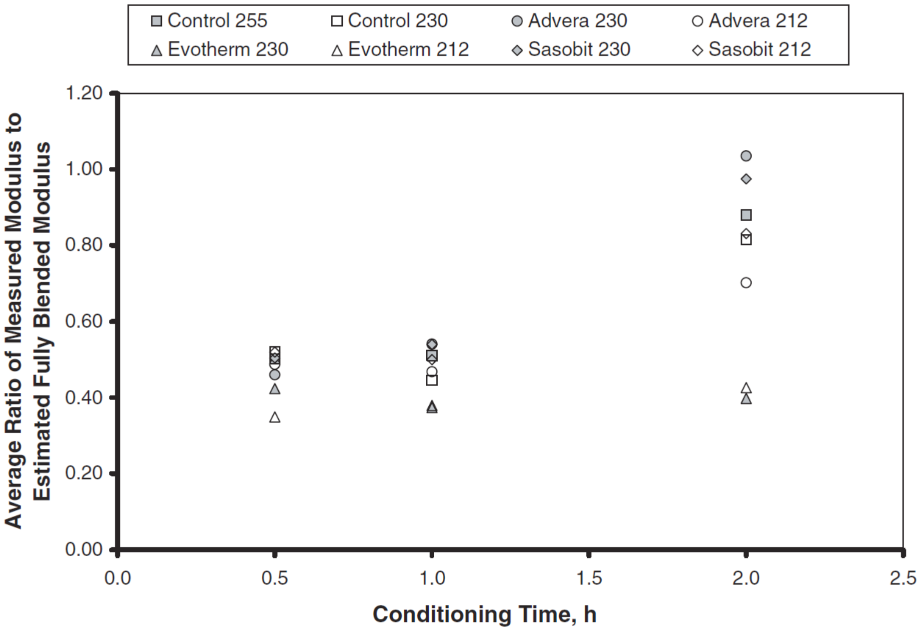


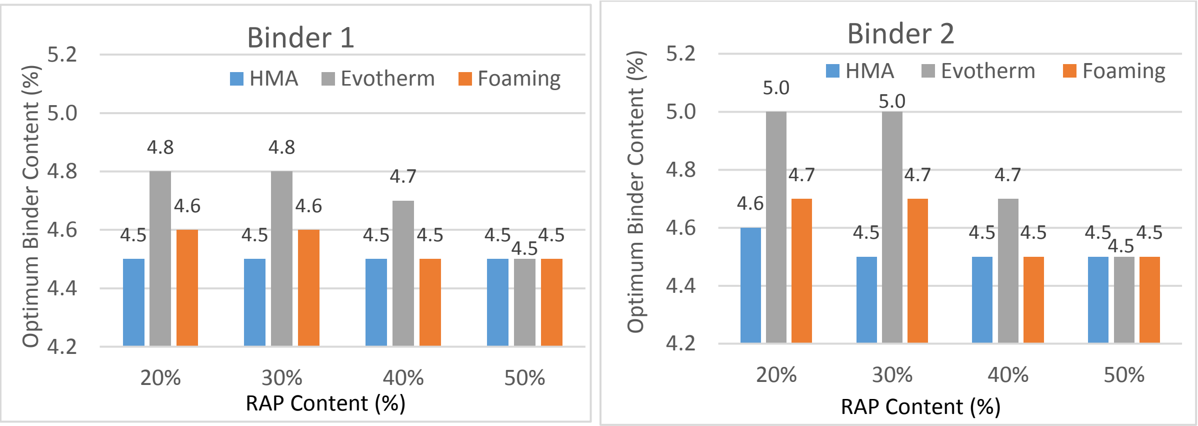
Figure 5 - Average ratio of measured modulus to estimated modulus at different levels of oven heating time (after Bonaquist 2011).

The data shown in Figure 5 shows an interesting trend. After two (2) hours of conditioning, the difference between the different mixes is very wide ranging from 0.44 to 1.0. Therefore, the question is whether the mixes that showed a ratio close to 1.0 are experiencing higher level of RAP blending, or the WMA technology used played a role? Furthermore, if the WMA technology played a role, is this role as a compaction lubricant or as a catalyst for RAP binder to diffuse? The experimental program of this study is designed to target these kinds of questions.

Gaitan et al. 2012 studied the effect of mixing temperature (260^{o}F & 315^{o}F), mixing duration (1 min & 5 min), and conditioning time (2 hr & 3 hr) on the blending of the RAP binder in a 25% RAP incorporating warm mix. Sasobit and Evotherm additives were used in the WMA mixes and compared to control mixes with no additives. All mixes were designed as gap graded mixes with virgin coarse aggregates and fine RAP aggregates. The author calculated the degree of blending (DOB) based on the G*/sin(delta) parameter for the recovered binder from the separated fine and coarse aggragates, where the larger the difference between the parameter for the fine aggregates versus the coarse aggregates means less blending had occurred. Gaitan et al. 2012 reported that the differences between the G*/sin(delta) value of the binder coating the fine and coarse aggregates increased considerably (85% for Evotherm, 96% for Sasobit, 151% for control) when increasing the mixing temerpatures from 260^{o}F to 315^{o}F. this was suggested to be partly caused by the stiffening effect of the elevated temperatures on the already aged RAP binder. This effect of the increased temperature was translated to a reduction of about 5% in the DOB. The author also stated the possibility of the breakdown of the WMA additive when used at higher temperatures than the design temperatures. On the other hand, extending the conditioning time from two (2) hours to three (3) hours was reported to increase the DOB by 8%.

Zhao et al. 2015 studied the binder blending of 50% RAP incorporating WMA mixes. The researchers used a variety of WMA additives including foaming, Sasobit, Rediset, Cecabase, and Evotherm. Gel permeation chromatography (GPC) was utilized as a means to determine the blending ratio, where blending ratio incorporated the ratio of the large molecular size (LMS) of the virgin aggregates over the LMS of the RAP aggregate. A gap graded mix was used to distinguish between the RAP and virgin aggregates. The researchers tested two (2) combinations of virgin/RAP aggregates. The first was a coarse virgin aggregates - medium RAP aggregates. The second was a medium virgin aggregates – fine RAP aggregates. The authors reported that in general, the non-foaming additives resulted in a slightly higher blending ratio than HMA mixed at same temperature as the WMAs (135°C). However, the blending ratio for these non-foaming additives was at the same time lower than that of HMA prepared at 165°C. On the other hand, the foaming WMA resulted in higher blending ratio than the HMA at both mixing temperatures (135°C & 165°C), nevertheless, the difference was not considerable. The results of the Zhao et al. 2015 study follows the same theme of the previous studies that high RAP content prepared at WMA temperatures is highly unpredictable, and may not achieve target quality measures set by the Superpave specification or other State DOT specifications.

A study made by Xiao et al. 2016 showed that for RAP contents of 20, 30 , 40, and 50%, WMA mixes made with Evotherm additive exhibited a higher optimum binder content (OBC) in comparison to conventional HMA and foamed WMA mixes. Figure 6 (a) and (b) show the results for the OBC values obtained by the researchers for two (2) binders.



(a) (b)

Figure 6 - Optimum binder content in WMA and HMA mixes for different RAP contents. (a) Binder 1 (b) Binder 2; (Xiao et al. 2016).

In Figure 6, an interesting relationship can be observed between the OBC and the RAP percentage, which is most evident in the Evotherm mix results. For lower RAP contents, the OBC is high, but as the RAP content increases, the OBC is reduced. It is worth mentioning that the researchers used PG 64-22 binders for RAP contents of 20% and 30% and a PG 58-28 for the higher percentages. In general the data may be explained by stipulating that when the RAP content is less than 40%, evotherm experiences lower blending, and as such, more optimum asphalt content is needed. This is because more virgin aggregate surface area is present in the system needing coating. As RAP content increases to 50%, there is less surface of virgin aggregates, and more area of contact between the heated virgin and RAP binders (even at WMA temperatures) to provide the needed lubrication for compaction.

It is important to note that there is no direct method that measures the binder replacement or the degree of blending. Rather, other "parameters" are used to indicate the DOB. For example the use of differences between the G*/sin(delta) values by Gaitan et al. 2012, use of "measured/estimated modulus" by Bonaquist et al. 2011, and the ratio of the LMS of virgin and RAP binders by Zhao et al. 2015. The absence of a unified methodology makes is difficult to compare results across different studies. Nevertheless, the literature clearly show that these surrogate methods are able to identify that the degree of blending between the RAP and virign binders for WMA is unpredictable and is dependent on many variables beside temperature, such as conditiong time, RAP content, WMA technology used, and amount of additive used.

2.4 Mechanical Performance of Warm Mix Asphalt

Because WMA is still a relatively new technology, very little long-term performance data are available. Studies, such as NCHRP Project 9-49A, are undergoing to assess whether WMA pavements are able to match the design life of HMA ones at comparable performance. Since WMA by design requires lower temperature range of application, the increase in RAP utilization and concentration can lead to concerns about mechanical stability of pavements. These concerns are mainly related to rutting performance, and moisture susceptibility of these mixes. In addition, some work on fatigue performance has been reported. The following section discusses these performance concerns.

2.5 Permanent Deformation

Resistance to rutting or permanent deformation of a pavement is a function of both the aggregate structure as well as the binder used in its production. Selecting aggregates with adequate interlock, strength and gradation is only half of the equation. While the other half depends on the binder's softness as well as on its ability to deform elastically. Production temperatures play a major role in assuring that the binder is aged adequately to resist rutting. However, in light of the reduced mixing and compaction temperatures associated with WMA mixes, there is a concern regarding the short-term aging of the binder. Where it is hypothesized that the lower temperatures result in softer mixes in which the binder has not stiffened sufficiently, WMA mixes might thus be more susceptible to permanent deformation problems in the form of rutting in the beginning of the service life of the pavement. Some studies were conducted on the effect of lowered production temperatures on the rutting related properties of binders with WMA additives.

Hanz et al. in 2011 examined the high-temperature (HT) grade of WMA incorporated binders subjected to lower rolling thin film oven (RTFO) aging temperatures of 120^{o}C and 105^{o}C. The authors reported a clear reduction in the in the HT grade of the binders when compared to the conventional 163^{o}C RTFO. However, the reduction was noted to be non-linear across the different temperatures and also being binder source dependent. Moreover, all WMA binders as well as the base binder failed the MSCR criteria for standard traffic at lowered RTFO aging temperatures. It is worth mentioning that the intermediate and low temperature grades were not significantly affected by the reduction in the short-term aging temperatures (Hanz et al. 2011). However, mixture samples conditioned at 105^{o}C before compaction were reported to have a significantly lower flow number (FN) in comparison with mixtures conditioned at 163^{o}C (Hanz et al. 2011). Gandhi (2008) also tested influence of WMA additives at lower rolling thin film oven aging temperatures on the properties of the binder. It was reported by the researcher that the lower RTFO temperatures caused a considerable reduction in the HT grade of the binders. These results support the concerns about the ability of WMA mixes to adequately perform without excessive permanent deformation.

The reported studies in the previous paragraphs did not incorporate RAP. Several studies looked into interaction between RAP and WMA on rutting performance. Reyes et al. 2009 reported an increase in the temperature susceptibility of foamed RAP mixes recovered from field cores with higher RAP percentages, as indicated by the change in the G*/sin(delta) values with temperature in the DSR results.

Solaimanian et al. in 2011 conducted a study on WMA+RAP up to 35% RAP content. They reported increase in the rut depth of WMA mixes with higher RAP percentages based on the Model Mobile Load Simulator (MMLS) when compared to HMA mixes at the same level of RAP. Goh et al. 2011 also explored the effect of lowered production temperatures on 15% RAP incorporating warm mixed porous asphalt mixtures, in a comparative study with similar hot mixed porous asphalt mixtures. The dynamic modulus (E*) was used to represent the stiffness and thus the rutting resistance of the mixes. The authors reported that virgin WMA mix had significantly lower modulus value than the HMA. However, the WMA mix showed a higher sensitivity to the addition of the 15% RAP to the mix, increasing to an approximately equal E* level as observed for the RAP-HMA mix. Zhao et al. 2012 studied the performance of plant produced foamed WMA mixes with 0%, 30%, 40%, and 50% RAP ratios, and compared the rutting level with that of similar HMA mixes. The authors reported that at 0% RAP, the HMA mix had better rutting resistance results than that of the WMA mix (according to the asphalt pavement analyzer (APA)). This was attributed by the authors to the lower aging level that the WMA is subjected to in production. However, the addition of RAP resulted in a greater relative improvement in the rutting resistance of the WMA mix than the HMA mix, however suggested that effect of RAP addition on the rutting resistance of WMA was stronger than its effect on the HMA.

Mogawer et al. 2012 examined the effect of the combination of 40% RAP and a wax-based WMA technology (SonneWarmix) on the stiffness of mixtures incorporating unmodified and polymer modified binders. The addition of RAP increased the stiffness of the unmodified mix, as indicated by the dynamic modulus, while the use of the WMA additive resulted in a reduction of the stiffness of both virgin and 40% RAP mixes. The reduction in stiffness was more profound for the polymer modified binder incorporating mixes.

Most of the reviewed literature on rutting resistance of RAP-WMA mixes suggests that even with the incorporation with RAP, WMA was still inferior to corresponding HMA mixes. Nevertheless, the literature also indicates that WMA mixes maybe more sensitive to the addition of RAP than conventional HMA mixes as was observed by some researchers such as (Goh et al. 2011 and Zhao et al. 2012).

Studies looking at field performance showed similar trends to those discussed above. Copeland et al. 2010 reported the extracted binder grading results of a 45% RAP-HMA mix and a 45% RAP-WMA mix were used to repave a portion of State Route 11 in Deland, Florida. The virgin binder used was a PG 52-28, while the post recovery binder in the HMA and WMA mixes were PG 64-16 and PG 52-22, respectively. The WMA mix was mixed and compacted at 40^{o}F lower than the HMA mix (310^{o}F mixing, 300^{o}F compaction) temperatures. Mixture testing revealed that RAP-WMA samples demonstrated slightly lower dynamic modulus values at intermediate and high temperatures compared RAP-HMA samples. The researchers also reported results of the Flow Number (FN) test. It was noted that the RAP-HMA mix achieved a higher flow number than the RAP-WMA mix. This suggested that the RAP-WMA mix is more prone to permanent deformation.

NCHRP Report 691 results showed that the rutting resistance, as measured by the Flow Number, of WMA mixes compacted at 260^{o}F and 215^{o}F (with and without 25% RAP) was lower than that of HMA mixes by an average of 40%. The highest flow numbers were obtained for the Sasobit mixes due to its effect on increasing the high temperature grade of the binder. Results from 5 field projects confirmed the laboratory data, where all WMA mixes from the field had lower flow number than that of the control HMA mixes, except for the case of Sasobit mixes which exhibited a constant increase in the rutting resistance. The lower short-term aging temperature was defined as the cause for the higher rutting susceptibility of the mixes (Bonaquist 2011).

Buss et al. 2015 reported on the SuperPave grading tests of several RAP incorporating (5%-20%) projects in Iowa. Each of these projects included both HMA and WMA mix sections. Chemical, organic, and foaming technologies were used in the production of the WMA sections. Binder recovery and grading was performed after two (2) years of service life. The differences in the high, intermediate, and low performance grades of the HMA in comparison with the WMA recovered binders of the same RAP levels were not significant. The stiffening effect of the RAP was overwhelming regardless of the softening effect the different WMA technologies used. The results indicated that the recovered binder from the WMA-RAP and HMA-RAP had the same rheological properties after two (2) years in service. This indicates that the WMA lower production temperature did not slow down aging of the binder.

2.6 Moisture Susceptibility

Moisture susceptibility may be defined as "*loss of strength, stiffness and durability due to the presence of moisture leading to adhesive failure at the binder–aggregate interface and/or cohesive failure within the binder or binder–filler mastic*" (Airey et al. 2008). The concern about moisture susceptibility is increased in WMA mixes due to the potential of insufficient drying of the aggregates at the lower mixing temperatures (Capitão et al. 2012, Kim et al. 2012, Martin 2014). Many studies have looked into the issue of moisture susceptibility of WMA mix, including few

NCHRP reports. NCHRP Report-763 includes a detailed review of the literature on the issue of moisture susceptibility (Epps-Martin 2014). The literature indicate that for virgin mixes, HMA mixes are less susceptible to moisture damage than WMA ones, whereas with the use of RAP the moisture susceptibility is reduced for both HMA and WMA (Solaimanian et al. 2011, Epps-Martin 2014). Other studies indicated that WMA technologies had no significant influence when compared with HMA mixes (Wasiuddin et al. 2008, Akisetty et al. 2009, Xiao et al. 2009, Punith et al. 2012). The inconsistent results observed by different researchers maybe attributed to the testing protocols that are currently adopted to characterize moisture susceptibility. These tests are empirical in nature and do not capture true material properties (Kim et al. 2012).

Solaimanian et al. 2011 showed that for both Sasobit^{TM} and Evotherm^{TM}, TSR values decrease with higher RAP content in the mix. At 0% RAP both Sasobit^{TM} and Evotherm^{TM} mixes have higher TSR values than the HMA mix, while for the 35% RAP mix, the HMA mixes have higher TSR values. It worth noting that for foamed WMA, the TSR value for mixes with RAP (15%, 35%) was lowered below 0.8 (Solaimanian et al. 2011). (Oliveira et al. 2012) also showed in that 50% RAP-HMA mix achieved a higher ITSR value in comparison with 50% RAP-WMA mix that utilized a surfactant as the WMA additive.

Mogawer et al. 2012 reported on the effect of a wax-based WMA additive with lowered mixing and compaction temperatures on the moisture susceptibility of unmodified and modified binder containing mixture specimens. The authors utilized the Hamburg Wheel-Tracking Device (HWTD) in the study. It was reported that the WMA mixes had lower moisture and rutting resistance than the corresponding control HMA mixes for both unmodified and modified binder mixtures. Although the use of 40% RAP improved the moisture susceptibility of the mixes, the combination of WMA with RAP still resulted in some reduction in the moisture resistance in comparison with HMA mixtures containing same amount of RAP.

Zhao et al. 2012 also investigated the moisture susceptibility of plant produced WMA and HMA mixes at different RAP ratios. It was observed that the TSR value of virgin HMA mix was higher than that of virgin the WMA mix. Incorporation of 30% RAP increased the TSR values for both mixes. Despite the relative increase in the TSR value of the WMA mix being somewhat greater, however, the eventual TSR value was still less than that of the HMA mix due to the lower initial TSR value for the virgin WMA. Results from the Hamburg wheel-tracking test also showed increase moisture resistance with higher RAP percentages. The relative reduction in the rut depth of saturated WMA mix was reported to be more significant than that of the HMA. This too implied a greater sensitivity of the WMA mix to RAP addition.

Two (2) large studies evaluated field performance of WMA containing RAP. NCHRP Report-691 included a moisture sensitivity evaluation for Sasobit, Advera, and Evotherm WMA mixes containing 25% RAP and compacted at 260^{o}F and 215^{o}F. The dry tensile strength was reported to be lower than that of the corresponding HMA mix (compacted at 310^{o}F) by an average of 25 psi. This lower value was consistent among all WMA technologies. Furthermore, the tensile strength ratio for all WMA mixes, excluding Evotherm, was reported to be lower than that of the HMA mixes. Also, most of the WMA mixes had a TSR ratio of less than 0.8 for both compaction temperatures included in the study, indicating susceptibility to moisture damage. The data was supported by field data from five (5) projects, where 9 out of 11 WMA mixes from the field as well as 2 out of 4 HMA mixes had TSR values of less than 0.8. Also, the majority of the WMA mixes had lower TSR values when compared with the HMA mixes (Bonaquist 2011).

NCHRP Report 763 was dedicated to the study of the moisture susceptibility of WMA mixes based on extensive testing of samples from four (4) projects in different climates. Two (2) of the projects included in the study incorporated RAP in the mixes (Iowa; 17% RAP with Evotherm & Sasobit) (New Mexico; 35% RAP with Evotherm 3G and Foaming). The researchers used IDT strength and TSR, wet MR stiffness and MR-ratio, Hamburg Wheel Track Test (HWTT) Stripping Inflection Point (SIP), and stripping slope to compare between the performances of the WMAs with corresponding HMA mixes. Based on the mentioned tests, (Epps-Martin 2014) reported that the WMA mixes were more susceptible to moisture damage before the first summer of aging. However, after the first summer, the WMA mixes were generally at least as good as the HMAs with respect to moisture resistance.

2.7 Fatigue Resistance

Fatigue resistance refers to the ability of pavements to withstand repeated loading by traffic while maintaining a crack free structure (Harvey et al. 1995). There are several testing protocols used to examine the fatigue life of asphalt concrete mixture such as the beam flexural fatigue test, the indirect tensile fatigue test, the semi-circular bending test, and other tests. Multiple studies were conducted to investigate the fatigue resistance of high RAP-WMA mixes and how it compared to that of conventional HMA mixes. In the following section some of these studies are reviewed:

Goh et al. 2011 compared the indirect tensile strength (ITS) of hot and warm mixed (Advera) porous asphalt concrete with and without 15% RAP. The authors reported that the ITS of the virgin HMA was higher than that of the WMA. However, with the incorporation of 15% RAP, the ITS of the HMA mix increased only slightly, while the ITS for the WMA exhibited a very significant increase, suggesting that the RAP-WMA mix may have a better fatigue resistance than the HMA-RAP.

Fatigue resistance of three (3) types of WMA mixes (Evotherm 3G, Sasobit, and Advera) was compared to that of a control HMA mix using the continuum damage theory in the NCHRP study reported by (Bonaquist 2011). Comparison of the fatigue half-life of the WMA mixes with the HMA mixes indicated similar fatigue resistance across all mixes, with the WMA performances fluctuating around that of the HMA mix depending on the compaction level (75 vs. 100 gyrations). Mogawer et al. in 2012 also studied the cracking susceptibility of WMA mixes incorporating 40% RAP for both unmodified and modified binder containing mixes with the use of the overlay tester (OT). The results reported by the researchers did not show one (1) single trend, but rather the effect of the WMA additive and the lower production temperatures was different based on the type of binder. While the WMA addition reduced the number of cycles to failure of the unmodified binder mix, it increased the number of cycles to failure for most modified binder mixes. Moreover, the inclusion of 40% RAP had an adverse effect on almost all mixes, but this negative effect was reduced by the combination of WMA additive and 40% RAP. The results indicated that the effect of WMA technologies should be studied with respect to the type of binders and other materials used in the mixes, where different combinations of materials result in different behaviors and performance levels (Mogawer et al. 2012).

In the study by Zhao et al. 2012, the fatigue resistance of high RAP- foamed WMA mixes was examined using the indirect tension test (IDT), as well as the four-point bending beam test. The two (2) parameters used in the IDT test, i.e. the dissipated creep strain energy ($DCSE_f$) as well as the Energy ratio (ER) provided contradicting results with regards to the effect of the RAP addition on the fatigue life. While the $DCSE_f$ indicated a slightly lowered fatigue resistance with higher RAP percentages, the ER parameter suggested the opposite. The beam test on the other hand, indicated a reduction in the fatigue life of HMA mix incorporating 30% RAP, while it indicated a higher number of cycles to failure for the 30% RAP incorporating WMA mix.

In another study by Shu et al. 2012, the $DCSE_f$ parameter of foamed WMA was reported to decrease with the inclusion of 30% RAP. The same behavior was reported for the corresponding HMA mix. The researchers attributed the lower $DCSE_f$ to the increased brittleness of the mixes that thus adversely affected the fatigue life of the mixes.

The studies conducted on the fatigue resistance of WMA mixes with high RAP contents did not seem to show a consensus on the effect of RAP incorporation on the fatigue life of WMA mixes. While some indicated the higher sensitivity of WMA than HMA mixes to RAP addition (Goh et al. 2011), other researchers pointed out the variability in fatigue resistance with respect to binder modification (Mogawer et al. 2012). Also, absence of a unified testing procedure seems to make the task of evaluating effect of WMA additives and RAP incorporation of fatigue performance more difficult.

2.8 Recommendation for Experimental Program

The literature shows that many questions need to be answered in order to implement high RAP content WMA as an acceptable mix for our pavements. The reported studies show many contradicting results with respect to the performance of the high RAP+WMA samples. The literature shows that improved performance can be traced to adequate mixing and compaction. Achieving an adequate level, however, appears to be a complex process. This is because it is dependent on the following reported factors:

1- Type of WMA technology and dosage,
2- Mixing temperature,
3- Conditioning time,
4- RAP content,
5- Asphalt binder source
6- Asphalt binder content, and
7- Mix design.

Based on the above list, the experimental program was designed to target these factors to quantify their effect with respect to PennDOT specifications and approved materials.

3 OBJECTIVES

The two (2) main objectives of the project are as follows:

First objective (Phase I): Identify the temperature dependency of RAP binder to be integrated and blended with the virgin asphalt binder during the mixing process. This is to verify that the calculated binder replacement is achieved when RAP is introduced at WMA temperatures.

To achieve this objective mixes are produced in light of the identified factors in the literature review to cover the full range of binder integrations. Volumetric analysis and densification curve indices are utilized to characterize the mixes.

Second objective (Phase II): Explore the damage resistance of WMA and RAP mixes at different levels of binder replacement. The mixing and compaction volumetric analysis cannot be the sole mechanism to justify the appropriateness of a given mix. This objective establishes the needed foundation to set allowable limits for mixing temperatures and RAP maximum contents for WMA pavements. This is extremely important at this stage, given PennDOT's increased utilization of WMA mixes.

Based on the results from Phase I of the study, statistically significant factors are selected to produce a subset of mixes that are used in Phase II of the study for the evaluation of the damage resistance of the mixes. The damage resistance is evaluated in terms of cracking resistance and rutting resistance. This is done through the Semi-Circular Bend (SCB) test at intermediate temperatures for cracking evaluation, and a densification curve index, for evaluation of the rutting resistance.

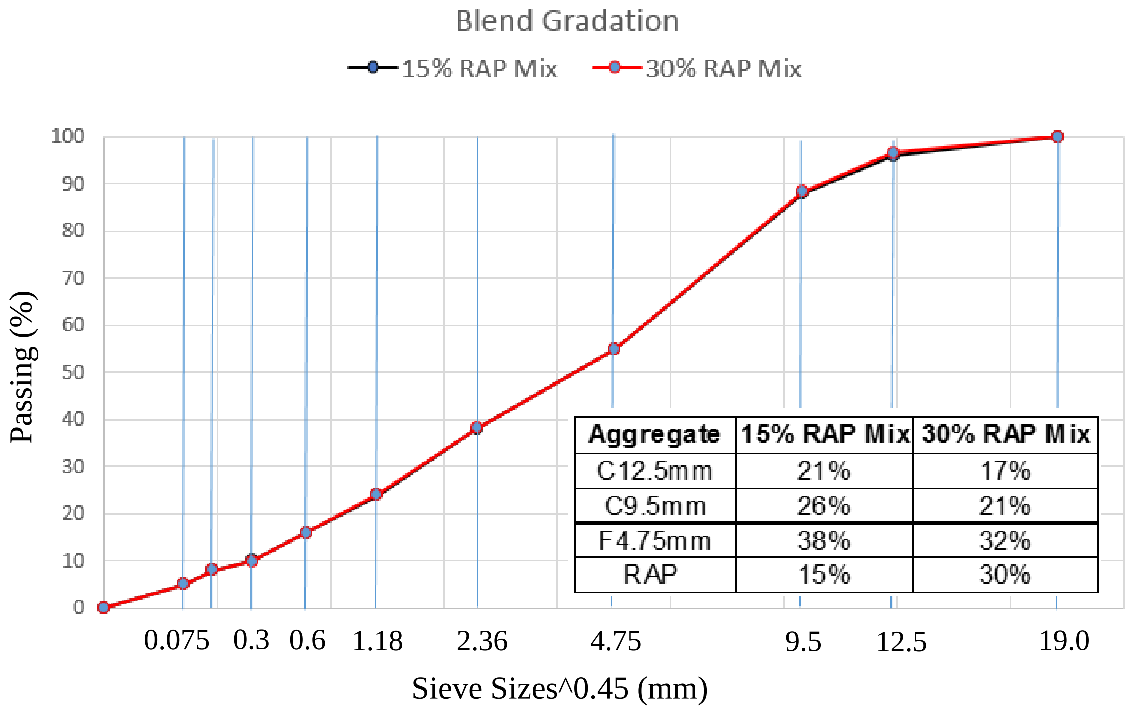
4 EXPERIMENTAL PROGRAM

In this section, the experimental programs for Phase I and Phase II of the project are presented separately. The same materials were used in the experimental program for both phases of the project as follows:

4.1 Materials

4.1.1 Aggregates

All of the aggregates used, including the two (2) RAP sources, were provided by suppliers in Pennsylvania. Three (3) virgin aggregates were utilized in combination with either of the RAP sources to produce all 36 mixes (4 control, and 32 combinations). Figure 7 shows the blend gradation for the 15% RAP containing mixes and the 30% RAP mixes. Every effort was made to minimize the differences between the blend gradations for the two (2) types of mixes. Figure 7 also shows the percentage of each aggregate in the two (2) types of mixes based on the RAP content.



Aggregate	15% RAP Mix	30% RAP Mix
C12.5mm	21%	17%
C9.5mm	26%	21%
F4.75mm	38%	32%
RAP	15%	30%

Figure 7 - Blend gradation and aggregate percentage for the 15% RAP and 30% mixes.

4.1.2 Asphalt Binder

The two (2) asphalt binder grades utilized in the study were supplied by a local supplier. Both the PG 64-22 and PG 58-28 binders are typical binders for use in Pennsylvania weather. Upon receipt of the binders from the supplier, viscosity tests were conducted on them to confirm the mixing and compaction temperatures that were reported by the supplier. The mixing and compaction temperatures were 155.5°C /144.5°C for the PG 64-22 and 151°C/139.5°C for the PG 58-28 binder.

4.1.3 WMA Additives

Two (2) WMA additives were used in this study. The first additive was Evotherm^{TM} 3G. This additive is a water-free chemical WMA technology that increases adhesion between the asphalt binder and the aggregate particles. Evotherm^{TM} 3G also permits mixing and compaction at reduced temperatures of approximately 28°C, while maintaining adequate workability and coating of the aggregate particles (Evotherm WMA 2013).

The other additive used was a bio-based chemical additive. The additive is referred to as Bio-HT in this study. The additive is claimed to allow for temperature reductions in the range of 30°C to 40°C. Bio-HT also facilitates compactability and enhances workability of the mixes.

Both of the additives were blended with the asphalt binder by the suppliers of the WMA technologies at a rate of 0.5% of the total binder weight in the mix. Further, in both HMA and WMA mixes, the binders were heated to the mixing and compaction temperatures as dictated by the viscosity tests, given that both of the additives used in the study do not affect the viscosity of the binder. The RAP and the virgin aggregates were heated to the HMA temperatures for the HMA mixes, and heated to 30°C lower temperatures for the WMA mixes, per the recommendations of the suppliers of the WMA additives.

4.2 Phase I Experimental Setup

The experimental program for Phase I was developed to incorporate the six (6) factors that were identified in the literature review process in a statistically balanced design. Each of the factors was considered in two (2) levels as follows:

- Binder grade: a PG 58-28 binder and PG 64-22 binder were used.
- Mixing and Compaction temperatures: HMA mixing temperature based on the viscosity tests of the binders, and a WMA temperature based on recommendations of the WMA additive suppliers.
- Conditioning duration: two (2) hours standard conditioning duration, and a prolonged four (4) hours conditioning prior to compaction of samples.
- RAP content: 15% as well as 30% by weight of the total mix.
- RAP source: RAP was obtained from two (2) PennDOT approved suppliers. RAP A of 5.45% binder content, and RAP B of 5.00% binder content.
- WMA additive type: the two (2) WMA technologies used were Evotherm™ and Bio-HT.

Four (4) control mixes were produced to obtain the Optimum Binder Content (OBC) for each RAP source and content. The OBCs among the four (4) control mixes did not vary by more than ±0.3%, where all OBCs were equal to 4.8±0.3%. These OBCs were used in production of the combinations of mixes developed for the experimental plan. Also, all mixes were produced such that the aggregate structure remained the same as that given for the PennDOT approved Job Mix Formula (JMF). According to the JMF, the mixes were designed for a traffic level of less than 30 million Equivalent Single Axle Load (ESALs), which corresponds to a design number of gyrations of 100.

The six (6) factors, each at two (2) levels, were combined in a fractional factorial design to allow for balanced representation of all factors. The total number of combinations was $2^{6-1} = 32$, where the "6" is the number of factors being studied, and "2" is the number of levels of each factor. Two (2) replicates were produced for each combination of the thirty-two (32) combinations. Figure 8 and Table 3 show a graphical representation of the experimental program, and the total number of mixes, including the four (4) control mixes, respectively.

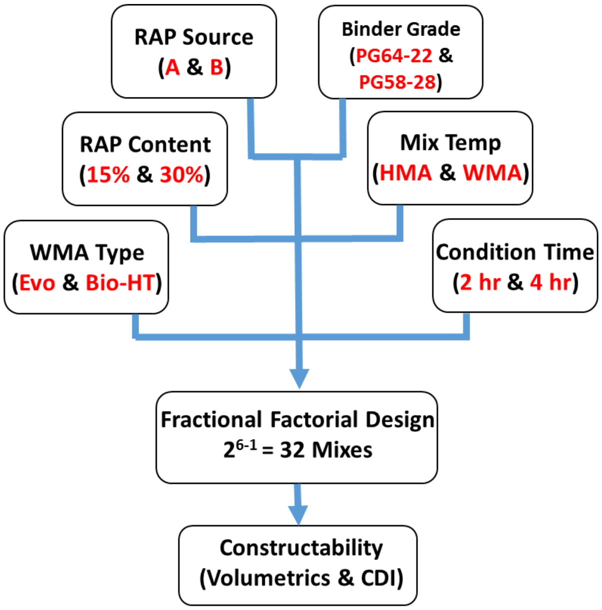


Figure 8 – Experimental program of Phase I of the study.

Table 3 - Combination of mixes produced per the experimental program.

Combination Number	RAP Content (%)	Mix Temperature (^{o}C)	Cond. Duration (min)	Binder Grade	RAP Source	WMA Technology
CONTROL-1	15%	HMA-Temp.	120	PG 64-22	B	-
CONTROL-2	15%	HMA-Temp.	120	PG 64-22	A	-
CONTROL-3	30%	HMA-Temp.	120	PG 64-22	B	-
CONTROL-4	30%	HMA-Temp.	120	PG 64-22	A	-
1	15%	WMA-Temp.	120	PG 64-22	B	Evotherm
2	15%	WMA-Temp.	120	PG 58-28	B	Bio-HT
3	15%	WMA-Temp.	120	PG 64-22	A	Bio-HT
4	15%	WMA-Temp.	120	PG 58-28	A	Evotherm
5	30%	WMA-Temp.	120	PG 64-22	B	Bio-HT
6	30%	WMA-Temp.	120	PG 58-28	B	Evotherm
7	30%	WMA-Temp.	120	PG 64-22	A	Evotherm
8	30%	WMA-Temp.	120	PG 58-28	A	Bio-HT
9	15%	HMA-Temp.	120	PG 64-22	B	Bio-HT
10	15%	HMA-Temp.	120	PG 58-28	B	Evotherm
11	15%	HMA-Temp.	120	PG 64-22	A	Evotherm
12	15%	HMA-Temp.	120	PG 58-28	A	Bio-HT
13	30%	HMA-Temp.	120	PG 64-22	B	Evotherm
14	30%	HMA-Temp.	120	PG 58-28	B	Bio-HT

Combination Number	RAP Content (%)	Mix Temperature (ºC)	Cond. Duration (min)	Binder Grade	RAP Source	WMA Technology
15	30%	HMA-Temp.	120	PG 64-22	A	Bio-HT
16	30%	HMA-Temp.	120	PG 58-28	A	Evotherm
17	15%	WMA-Temp.	240	PG 64-22	B	Bio-HT
18	15%	WMA-Temp.	240	PG 58-28	B	Evotherm
19	15%	WMA-Temp.	240	PG 64-22	A	Evotherm
20	15%	WMA-Temp.	240	PG 58-28	A	Bio-HT
21	30%	WMA-Temp.	240	PG 64-22	B	Evotherm
22	30%	WMA-Temp.	240	PG 58-28	B	Bio-HT
23	30%	WMA-Temp.	240	PG 64-22	A	Bio-HT
24	30%	WMA-Temp.	240	PG 58-28	A	Evotherm
25	15%	HMA-Temp.	240	PG 64-22	B	Evotherm
26	15%	HMA-Temp.	240	PG 58-28	B	Bio-HT
27	15%	HMA-Temp.	240	PG 64-22	A	Bio-HT
28	15%	HMA-Temp.	240	PG 58-28	A	Evotherm
29	30%	HMA-Temp.	240	PG 64-22	B	Bio-HT
30	30%	HMA-Temp.	240	PG 58-28	B	Evotherm
31	30%	HMA-Temp.	240	PG 64-22	A	Evotherm
32	30%	HMA-Temp.	240	PG 58-28	A	Bio-HT

4.2.1 Densification Curve Indices

The Construction Densification Index (CDI) was derived from the densification curves of the mixes to assist in analysis of the results. The CDI is a measure of the energy required to achieve a density of 92% upon compaction of the mix. The CDI is calculated as the area under the densification curve between the eighth (8th) gyrations mark and the number of gyrations corresponding to a % Gmm of 92%. A lower CDI indicates that the mix is easier to compact to achieve that target density, thus being desirable. However, if the CDI is too low, it may be a sign of a tender mix (Faheem et al 2005). The CDI can also be considered as an indicator of binder replacement. As binder replacement increases, CDI is expected to improve.

Another index that can be derived from the densification curves is the Traffic Densification Index (TDI). The TDI is area under the densification curve between 92% Gmm and 98% Gmm. The TDI thus relates to the densification that takes place during the service life of the pavement under traffic loading. A high TDI value is more desirable, where more traffic load can be carried by the pavement before reaching the critical density of 98%. This is an indication of the mix being more stable. Worth mentioning that the TDI was found to correlate very well with rutting resistance of asphalt concrete mixes (Faheem et al 2005). Figure 9 provides a graphic representation of the CDI and TDI calculation.

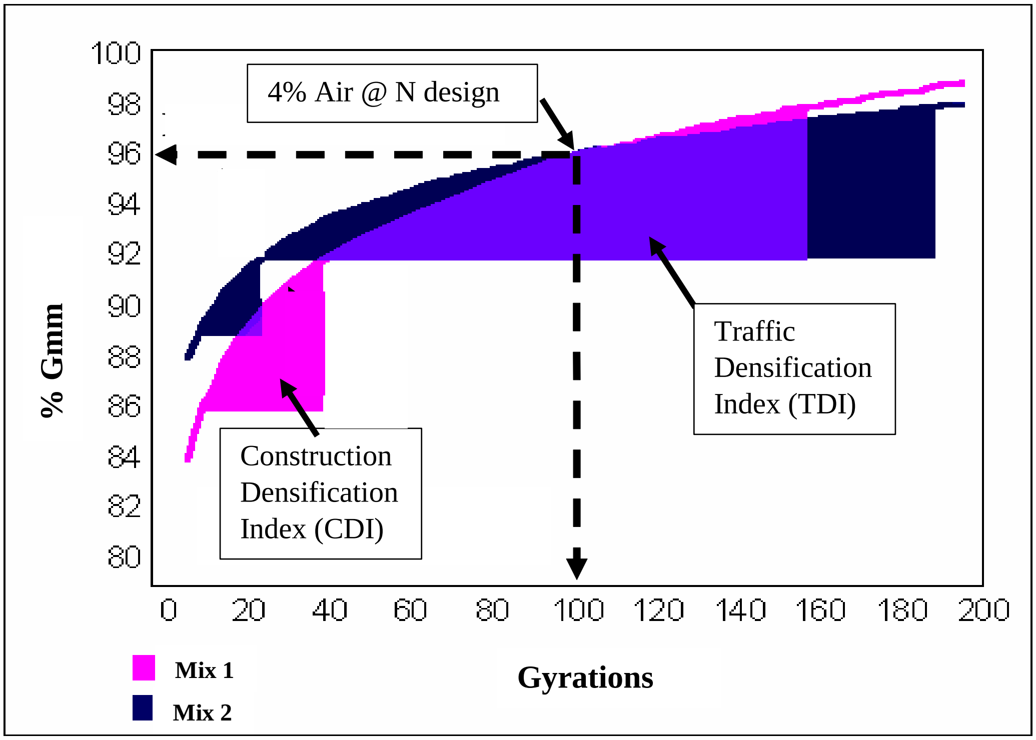


Figure 9 - Calculation of CDI and TDI from the densification curve (adapted from Faheem et al 2005).

Figure 9 also shows that different mixes may all meet the required volumetric properties, while having different CDI and TDI values. This indicates that the use of volumetric properties may not be sufficient for differentiation between mixes with different workability and stability characteristics.

4.3 Phase II Program

Analysis of the results of phase I of the study that included all six (6) factors lead to the elimination of the “WMA type” and “conditioning time” factors in the design process of Phase II of the study. The four (4) remaining factors were included in the experimental program of Phase II due to their statistically significant effect on the volumetric properties and constructability of the mixes. These factors are the RAP source, RAP content, mixing/compaction temperature, and binder grade.

A balanced full factorial design was used for the four (4) factors, where each factor was considered in the same two (2) levels used in Phase I of the study. The resulting number of combinations is therefore 2^4 = 16 combinations. Similar to Phase I of the study, the four (4) control mixes were also added to the experimental program. This was done to serve as a baseline to which the mechanical stability results for the other combinations is compared. Table 4 provides information on the number of mixes and the combination of factors in each mix. Also, Figure 10 presents a graphical representation of the experimental program of Phase II of the project.

Table 4 – Experimental program for the mechanical stability study.

Combination Number*	Binder Grade	RAP Content (%)	RAP Source	Mixing Temperature (ºC)
control-1	PG 64-22	15%	B	HMA-Temp.
control-2	PG 64-22	15%	A	HMA-Temp.
control-3	PG 64-22	30%	B	HMA-Temp.
control-4	PG 64-22	30%	A	HMA-Temp.
1	PG 64-22	15%	B	WMA-Temp.
2	PG 64-22	15%	B	HMA-Temp.
3	PG 64-22	15%	A	WMA-Temp.
4	PG 64-22	15%	A	HMA-Temp.
5	PG 64-22	30%	B	WMA-Temp.
6	PG 64-22	30%	B	HMA-Temp.
7	PG 64-22	30%	A	WMA-Temp.
8	PG 64-22	30%	A	HMA-Temp.
9	PG 58-28	15%	B	WMA-Temp.
10	PG 58-28	15%	B	HMA-Temp.
11	PG 58-28	15%	A	WMA-Temp.
12	PG 58-28	15%	A	HMA-Temp.
13	PG 58-28	30%	B	WMA-Temp.
14	PG 58-28	30%	B	HMA-Temp.
15	PG 58-28	30%	A	WMA-Temp.
16	PG 58-28	30%	A	HMA-Temp.

*The control mixes do not contain a WMA additive.

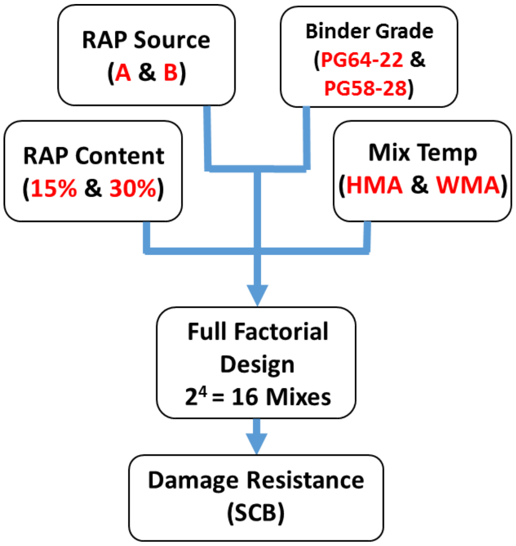


Figure 10 – Experimental program of Phase II of the program.

All produced mixes were conditioned for two (2) hours prior to compaction. The decision was also made to use Evotherm^{TM} WMA technology to produce all combination of WMA mixes (excluding the control mixes). Evotherm^{TM} was chosen over the Bio-HT additive used in phase I of the study for reasons related to the availability of the additive and ease of procurement.

The damage resistance of the mixes was evaluated through the use of the Semi-Circular Bend (SCB) test at intermediate temperatures .

4.3.1 Fracture Resistance Test

The fracture resistance testing process followed the procedure developed at the University of Illinois at Urbana-Champaign by Al-Qadi et al (2015). In the following sections details about the production and testing scheme is provided:

4.3.1.1 Sample Preparation:

Based on the recommendations of Al-Qadi et al (2015), all mixes were produced at a target air void content of 7±0.5 %. One gyratory compacted sample at a height of 160 mm was produced for each mix. After verifying that the target air void was obtained, the cylindrical samples were cut to obtain four (4) half-discs for the Semi-Circular Bend (SCB) test. The cutting process was made with the use of a circular diamond blade. At first, the top and bottom parts of each cylinder were cut and removed. The middle part of the cylindrical sample was then cut to obtain two (2) identical discs of 50±1 mm in thickness. Each disc was cut in half, providing a total number of four (4) half-discs to be used for the testing. A notch was made in the middle of each SCB test specimen such that the depth of the cut was 15±1 mm and the width was 1.5±0.1 mm as shown in figure 11. Upon completion of the cutting process, the test specimens were placed in a water bath set at a temperature of 25^{o}C for 2-2.5 hours prior to testing.

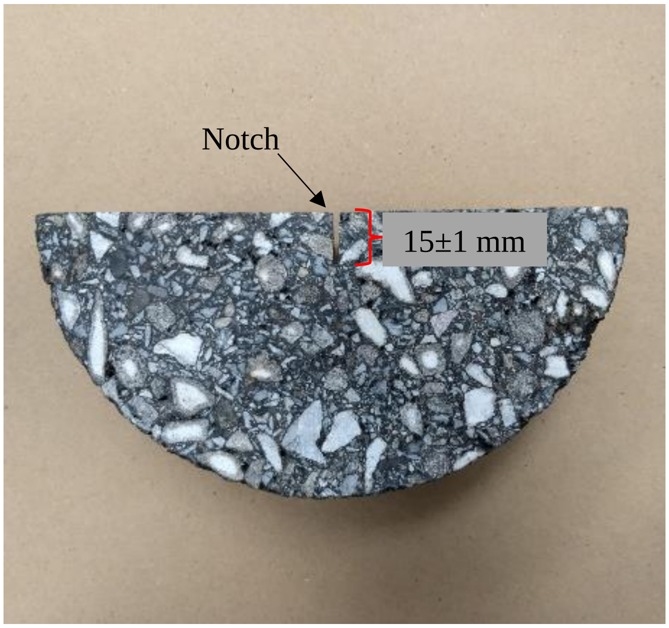


Figure 11 - SCB sample prepared for testing.

4.3.1.2 Semi-Circular Bend (SCB) Test:

The SCB test is a three (3) point bend test that is used to measure the ability of asphalt mixture samples to resist crack formation. The test can be used to characterize crack propagation at both intermediate and low temperatures. For the purposes of this study, the test is conducted at intermediate temperature. This is done to examine the effect, if any, of the interaction of high RAP contents and WMA mixes on the mix mechanical stability.

A MTS universal testing machine was used to perform the test. The two (2) roller supports were lubricated prior to the start of the test to reduce friction between the sample and the supports during the test. An initial seating load of 0.1 kN was applied on the samples to assure contact between the loading cell of the machine and the surface of the sample. After confirming contact, the samples were loaded in a displacement-controlled mode at a loading rate of 50 mm/min. Loading was continued until the force reading dropped to a value equal to the seating load. The force readings and the load-line-displacement from the machine actuator were recorded and plotted to allow for the calculation of the fracture energy and flexibility index of the mixes.

Figure 12 presents a typical SCB test graph. The upward part of the force-displacement curve up to the peak force represents the sample resistance to crack propagation. Once the peak force is reached and failure occurs, the crack starts to propagate throughout the sample. The slope of the downward curve represents the velocity of the crack propagation. Higher slope values are indicative of more brittle failures, while a lower slope is obtained for more ductile failures. The area under the curve is calculated and denoted as the work of fracture in (Joules). The work of fracture is used to calculate the fracture energy in (Joules/m^2) as follows:

$$Fracture\ Energy = \frac{Work\ of\ Fracture}{Thickness\ \times Ligament\ length}$$

In addition to the fracture energy, the flexibility index is calculated by dividing the fracture energy by the slop of the downward curve at the inflection point. Higher flexibility index values indicate flexible mixes with more ductile failures.

$$Flexibility\ Index = \frac{Fracture\ Energy}{|Slope|}$$

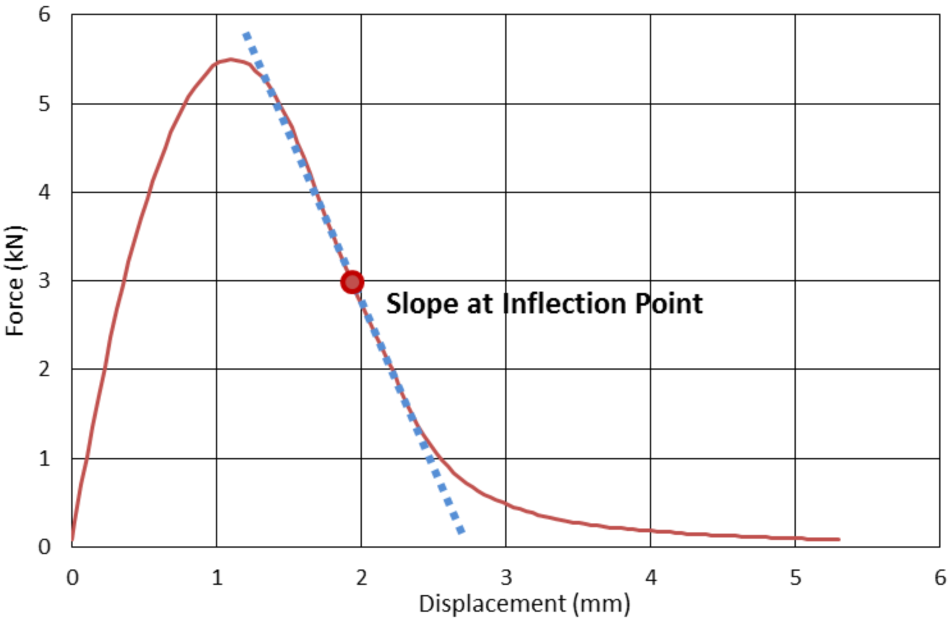


Figure 12 – Sample of the SCB test results.

5 RESULTS AND DISCUSSION

5.1 Phase I Results

In the following sections, the results obtained from Phase I of the study are presented.

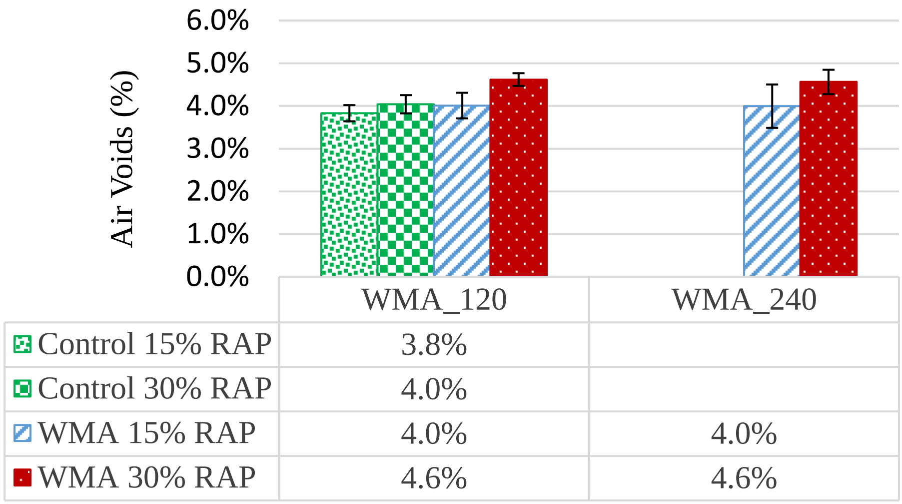
5.1.1 Volumetrics and Construction Densification Index (CDI) Results

The results from the thirty-two (32) mixes produced in Phase I of the study were analyzed in terms of the effect of the six (6) factors on the volumetric properties (air content), workability of the mixes as measured by the CDI.

5.1.1.1 Effect of RAP Content

This section focuses on evaluating the effect of RAP content on the observed workability related characteristics of the mixes. Figure 13 shows the air content values at Ndes (Va) at the two (2) levels of RAP studied. The figure also shows the control mix (No WMA) as reference at 15% and

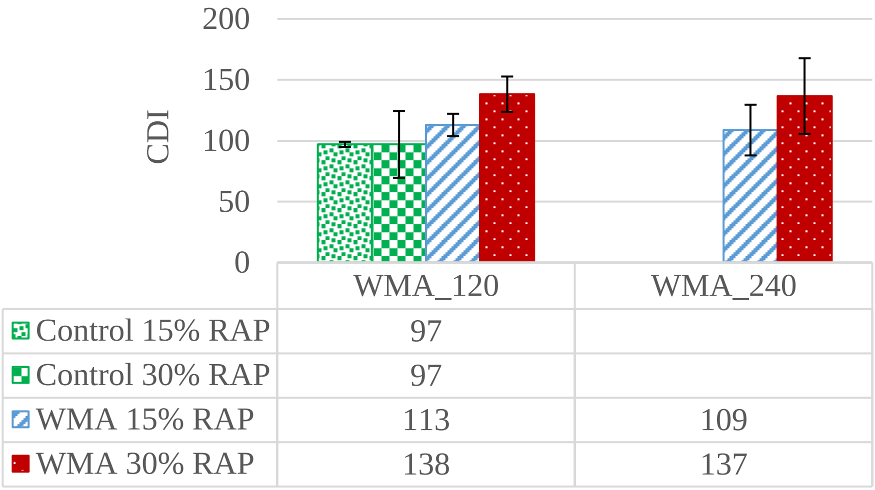
30% RAP. It includes the air content for the WMA mixes after 2 and 4 hours of conditioning in the oven before compaction for the same RAP levels.



	WMA_120	WMA_240
▨ Control 15% RAP	3.8%	
▨ Control 30% RAP	4.0%	
▨ WMA 15% RAP	4.0%	4.0%
🟥 WMA 30% RAP	4.6%	4.6%

Figure 13 - Air content for WMA mixes at 15% and 30% RAP

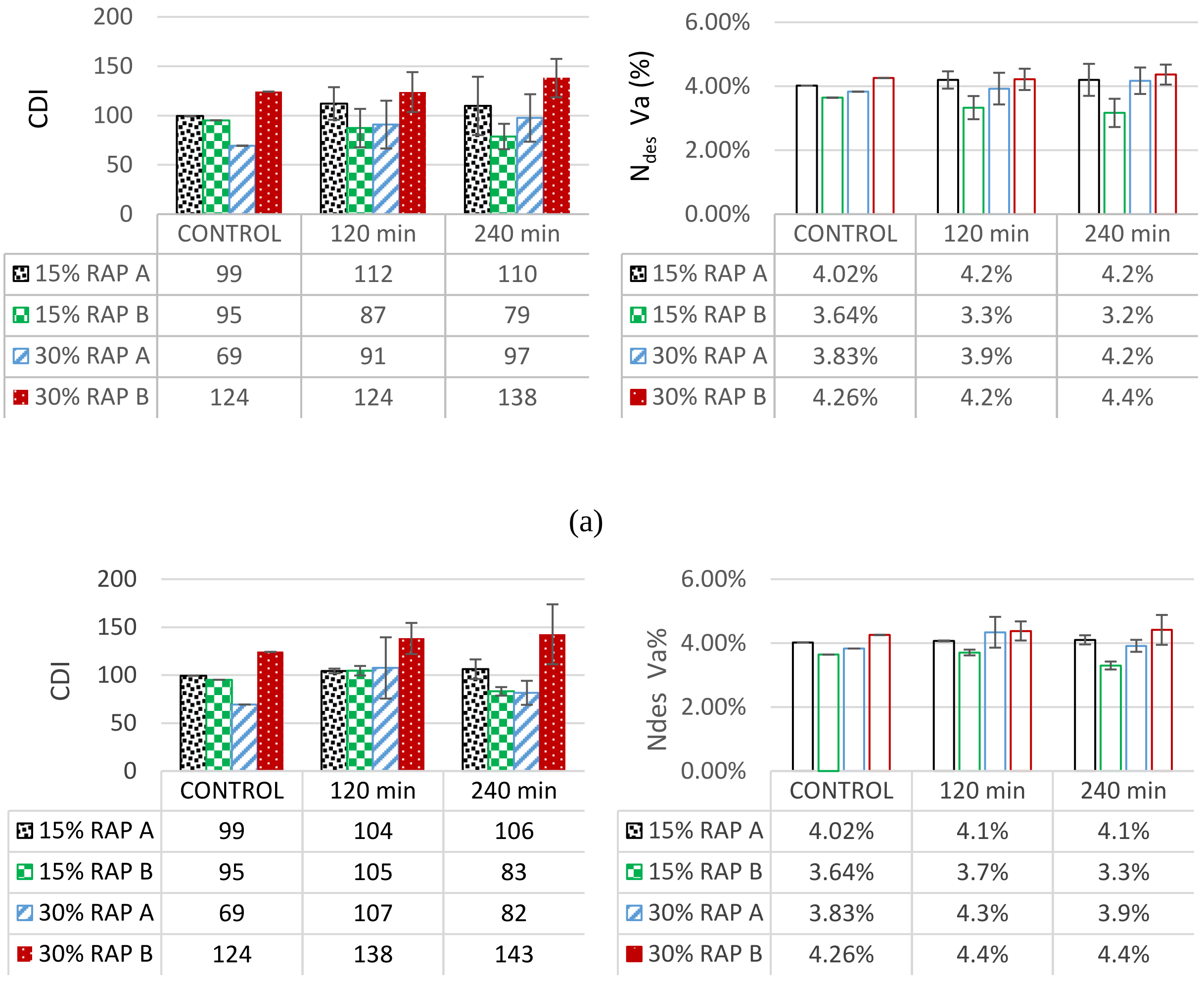
In Figure 13, the 15% RAP mixes behaved on average in a similar manner to the control mixes. The 30% RAP mixes show some increase in the air content at WMA temperatures. For the WMA samples, at 15% RAP air content (Va%) at Ndes is achieved. Increasing the RAP to 30% show an average increase in the Va%. Increasing the conditioning time where the mixes are kept at compaction temperature for extended time show no change in the mix average volumetric data. The CDI date in Figure 14 confirms the same trend.



	WMA_120	WMA_240
▨ Control 15% RAP	97	
▨ Control 30% RAP	97	
▨ WMA 15% RAP	113	109
🟥 WMA 30% RAP	138	137

Figure 14 - CDI for WMA mixes at 15% and 30% RAP under Different Conditioning Times

Figure 15 (a) and (b) show the effect of conditioning duration on the CDI and Va values for the PG58 and PG64 binder mixes, respectively. The effect of the conditioning duration is unclear, as no apparent trend can be identified for the results obtained for the two (2) conditioning durations considered in this study. In general, the 30% RAP mixes show that the control samples are more workable than the WMA mixes conditioned for 120 minutes. However, the same trend is not observed in the 15% RAP mixes. To isolate and identify the factors of significant influence on the mix workability, statistical analysis is performed on these results and presented in this report.

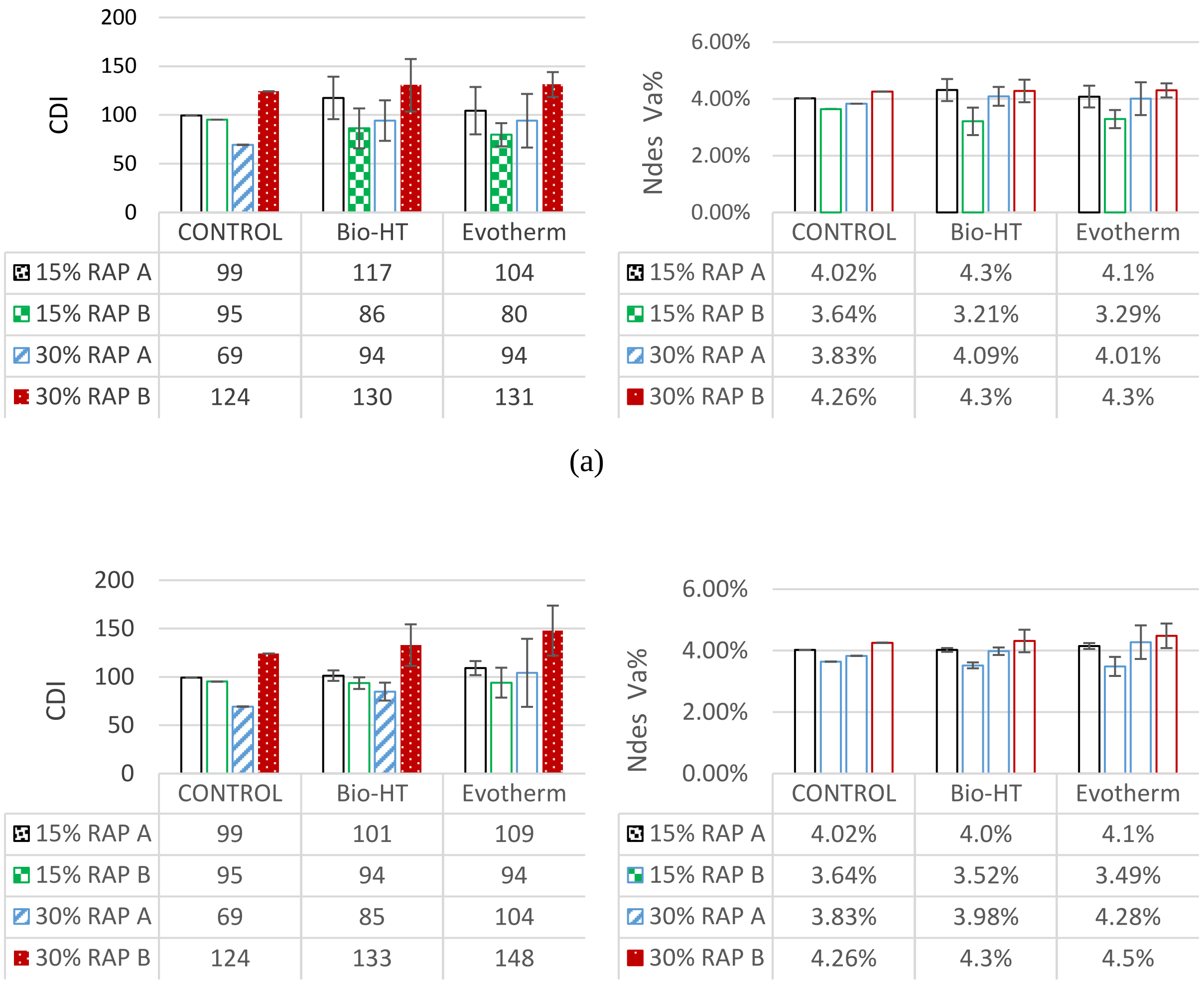


(a)

(b)

Figure 15 – Influence of mix conditioning duration on CDI and Va values. (a) PG 58-28, (b) PG 64-22.

Figure 16 shows the impact of the WMA additive type on average CDI and Va values for the different mixes. The results show mixed trends in terms of sensitivity to WMA additives. Some of the 30% RAP mixes show average reduction in workability when compared to the control mixes, but this reduction is within the range of availability. The results indicate that the compaction of the mixes is highly dependent on the RAP type than the WMA additive.



	CONTROL	Bio-HT	Evotherm
▣ 15% RAP A	99	117	104
▣ 15% RAP B	95	86	80
▨ 30% RAP A	69	94	94
■ 30% RAP B	124	130	131

	CONTROL	Bio-HT	Evotherm
▣ 15% RAP A	4.02%	4.3%	4.1%
▣ 15% RAP B	3.64%	3.21%	3.29%
▨ 30% RAP A	3.83%	4.09%	4.01%
■ 30% RAP B	4.26%	4.3%	4.3%

(a)

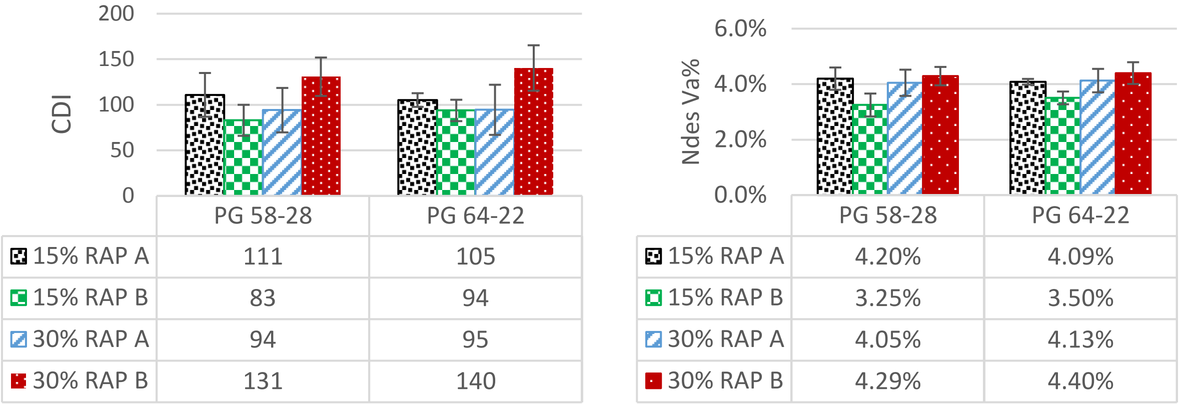
	CONTROL	Bio-HT	Evotherm
▣ 15% RAP A	99	101	109
▣ 15% RAP B	95	94	94
▨ 30% RAP A	69	85	104
■ 30% RAP B	124	133	148

	CONTROL	Bio-HT	Evotherm
▣ 15% RAP A	4.02%	4.0%	4.1%
▣ 15% RAP B	3.64%	3.52%	3.49%
▨ 30% RAP A	3.83%	3.98%	4.28%
■ 30% RAP B	4.26%	4.3%	4.5%

(b)

Figure 16 – Impact of the WMA additive type on CDI and Va values. (a) PG 58-28, (b) PG 64-22.

Figure 17 shows the effect of the binder grade on compaction values. No apparent binder dependent pattern can be detected. The two (2) binders seem to be producing similar results. Statistical analysis of the factorial design is conducted to assist in revealing more about the influence of the binder grade, if any.



	PG 58-28	PG 64-22
15% RAP A	111	105
15% RAP B	83	94
30% RAP A	94	95
30% RAP B	131	140

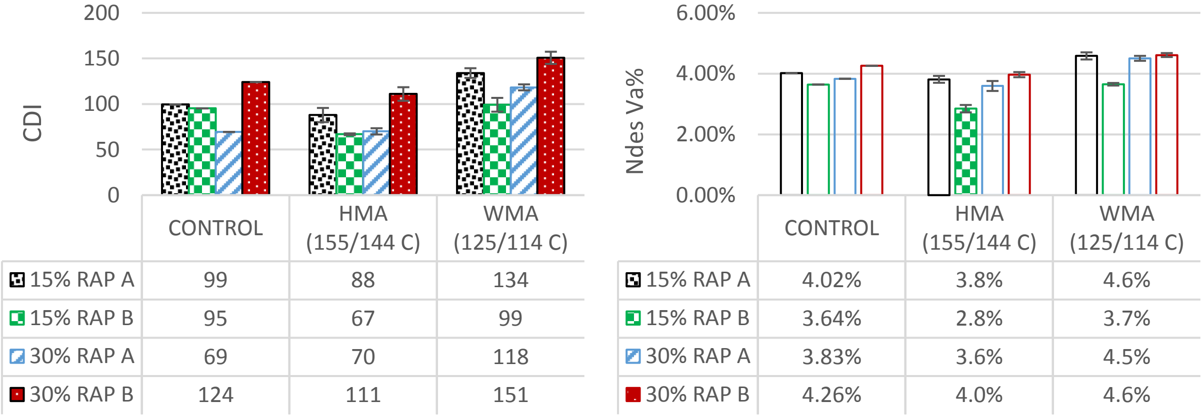
	PG 58-28	PG 64-22
15% RAP A	4.20%	4.09%
15% RAP B	3.25%	3.50%
30% RAP A	4.05%	4.13%
30% RAP B	4.29%	4.40%

Figure 17 – Effect of the binder grade on the average CDI and Va values.

5.1.1.2 Effect of Production Temperature

Figure 18 (a) and (b) show the results of compaction at the different levels of production temperatures. The values shown in Figure 18 are average values for all mixes within each category. For example, the results shown for a 15% RAP A mix include an average of all mixes produced with 15% of RAP A regardless of the conditioning duration or the WMA type.

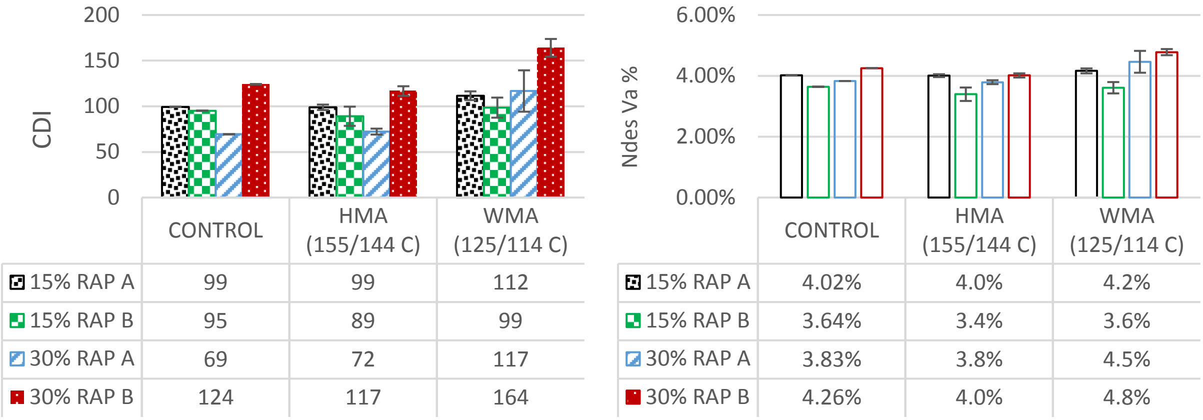
It can be seen from Figure 18 that all mixes produced at WMA temperatures are harder to compact compared to those produced at HMA temperatures. Also, mixes produced with softer binder (PG 58-28) show more sensitivity to the reduction in the temperatures, even at 15% RAP contents. The PG 64-22 binder mixes show slight increase at the 15% RAP content and large increase at 30% RAP content. Comparing control mixes and WMA mixes produced at HMA temperature show on average similar or lower compaction. This trend is lost at WMA temperature. This indicates that using WMA additives at HMA temperatures as compaction aids result can enhance compaction at RAP contents up to 30%.



	CONTROL	HMA (155/144 C)	WMA (125/114 C)
15% RAP A	99	88	134
15% RAP B	95	67	99
30% RAP A	69	70	118
30% RAP B	124	111	151

	CONTROL	HMA (155/144 C)	WMA (125/114 C)
15% RAP A	4.02%	3.8%	4.6%
15% RAP B	3.64%	2.8%	3.7%
30% RAP A	3.83%	3.6%	4.5%
30% RAP B	4.26%	4.0%	4.6%

(a)



(b)

Figure 18 - Effect of production temperatures on CDI. (a) PG 58-28, (b) PG 64-22.

Table 5 shows the percent increase in the compaction effort as measured by the CDI values when the temperatures are dropped to WMA production temperatures. The highest increase is seen in the 30% RAP A mix produced with the PG58-28 binder at approximately 70% increase in the CDI value or 70% reduction in the workability. The PG58-28 binder show consistently higher level of reduction in workability for all the mixes. The PG 64-22 binders show higher reduction in workability for the 30% RAP regardless of the source. This shows that the interaction of the temperature, binder grade, and RAP content plays a significant role in controlling mix workability.

Table 5 – Percent increase in CDI for the WMA temperatures in comparison with HMA temperatures.

RAP Source and Percentage	Binder Grade	
	PG 58-28	PG 64-22
15% RAP A	52%	13%
15% RAP B	48%	11%
30% RAP A	69%	62%
30% RAP B	36%	41%

In order to highlight the effects of all the factors and their interaction on the mix constructability, full factorial statistical analysis is required. This eliminates the bias that could be created by the graphical representation of the data. Section 5.1.2 shows the details of this analysis.

5.1.2 Statistical Analysis for Phase I Results

The experimental design follows fractional factorial format. This allows for comprehensive analysis for each of the variables and their interactions in a quantitative manner. The analysis was conducted after assuring that all the statistical conditions are met. These include normality of the data, randomness of the residuals, and independence of the variables.

5.1.2.1 Influence on Va at Design Number of Gyrations (N_{des})

The fractional factorial analysis with air content as the dependent variable yielded the following results.

```
Term                        Effect     Coef  SE Coef  T-Value  P-Value   VIF
Constant                              3.9875   0.0343   116.37    0.000
RAP Source                 -0.2550  -0.1275   0.0343    -3.72    0.001  1.00
RAP Content                 0.4575   0.2287   0.0343     6.68    0.000  1.00
Temperature                -0.6175  -0.3087   0.0343    -9.01    0.000  1.00
RAP Source*RAP Content      0.5100   0.2550   0.0343     7.44    0.000  1.00
Temperature*Binder Grade    0.1675   0.0838   0.0343     2.44    0.023  1.00
```

The significance level for the analysis corresponds to p-value of 0.1 or less. This means that the conditioning time and binder grade do not show significant effect on the mixtures air content at N_{des}. This p-value is arbitrary selected by the research team given the level of variability in the mix results. The most influencing factor is the production temperature. The results show that as the temperature increases, the air content significantly decreases. This is a logical trend. The results shown above suggest that when the production temperature is increased from WMA to HMA levels, the Va would drop by and average value of 0.62%.

The interaction between RAP source and RAP content is the second most significant factor influencing air content. Given that the RAP source is a surrogate to binder content (and RAP binder grade) within the RAP, then the results from the statistical analysis are logical. The analysis shows that as the RAP source change and the RAP content increase, constructability becomes more difficult.

In summary, the most influencing factors on the measured air content are ranked by order of level of significance:

1- Production Temperature (Factor↑ ➔ Air↓)
2- Interaction between RAP source and content (Factor↑ ➔ Air↑)
3- RAP content (independently) (Factor↑ ➔ Air↑)
4- RAP source (independently) (Factor↑ ➔ Air↓)
5- Interaction between Temperature and Binder grade (Factor↑ ➔ Air↑)

5.1.2.2 Influence on CDI

In this section the analysis is conducted on the influence of the factors on the constructability index.

```
Term                     Effect    Coef  SE Coef  T-Value  P-Value   VIF
Constant                         106.69     2.06    51.83    0.000
RAP Source                10.87    5.44     2.06     2.64    0.015  1.00
RAP Content               16.50    8.25     2.06     4.01    0.001  1.00
Temperature              -35.00  -17.50     2.06    -8.50    0.000  1.00
RAP Source*RAP Content    30.25   15.13     2.06     7.35    0.000  1.00
RAP Content*Temperature   -9.88   -4.94     2.06    -2.40    0.025  1.00
```

According to the analysis, the CDI is most significantly influenced by the production temperature such that as the temperature increases, the CDI decreases. The average effect of reducing the production temperature is on average a 30% increase in compaction effort. Similar to the analysis for the air content, the interaction between RAP source and RAP content are highly significant. The trend is also similar to that of the air content.

In summary, the most influencing factors on the measured CDI are ranked by order of level of significance:

1- Production Temperature, (Factor↑ ➔ CDI↓)
2- Interaction between RAP source and content (Factor↑ ➔ CDI↑)
3- RAP content (independently) (Factor↑ ➔ CDI↑)
4- RAP source (independently) (Factor↑ ➔ CDI↑)
5- Interaction of RAP content and Temperature (Factor↑ ➔ CDI↓)

The listed significant factors and their influence are expected and logical. The interesting finding is that the WMA technology is not a significant factor. This means that both technologies used are statistically similar as to their effect on CDI.

5.1.3 Temperature Dependency of RAP-WMA Mixes

Figure 19 shows the average air content as a function of the RAP content for the thirty-two (32) mix combinations produced in Phase I of the study. The figure shows that the mixing and compaction temperatures have a significant effect on the volumetric properties of the produced mixes. Also, the increase in the RAP content increase the air voids significantly. This was also confirmed by the statistical analysis that was performed on the results of Phase I.

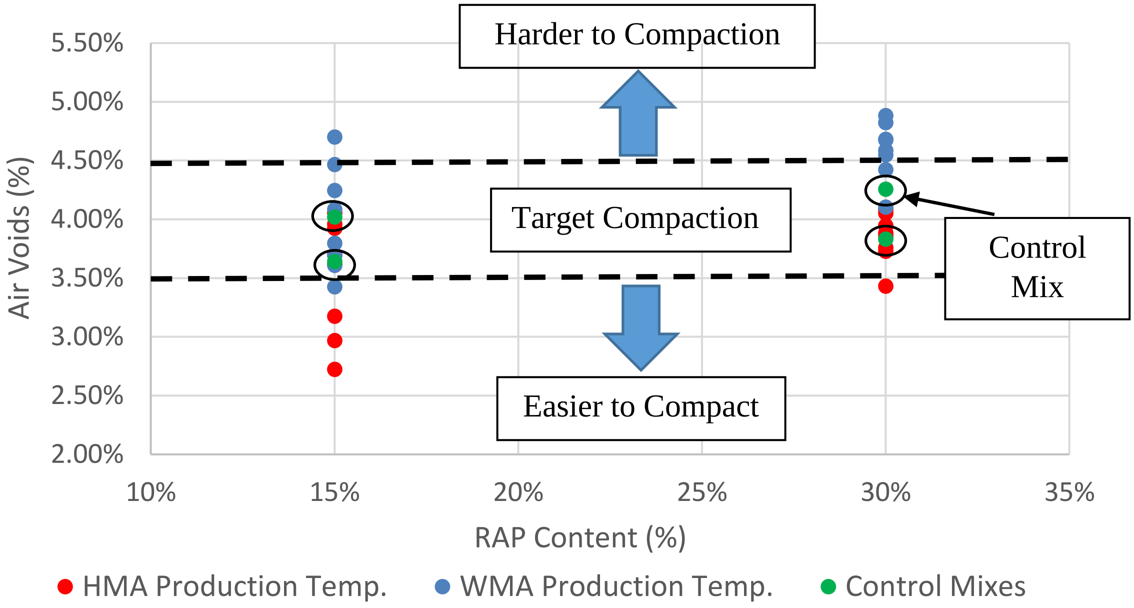


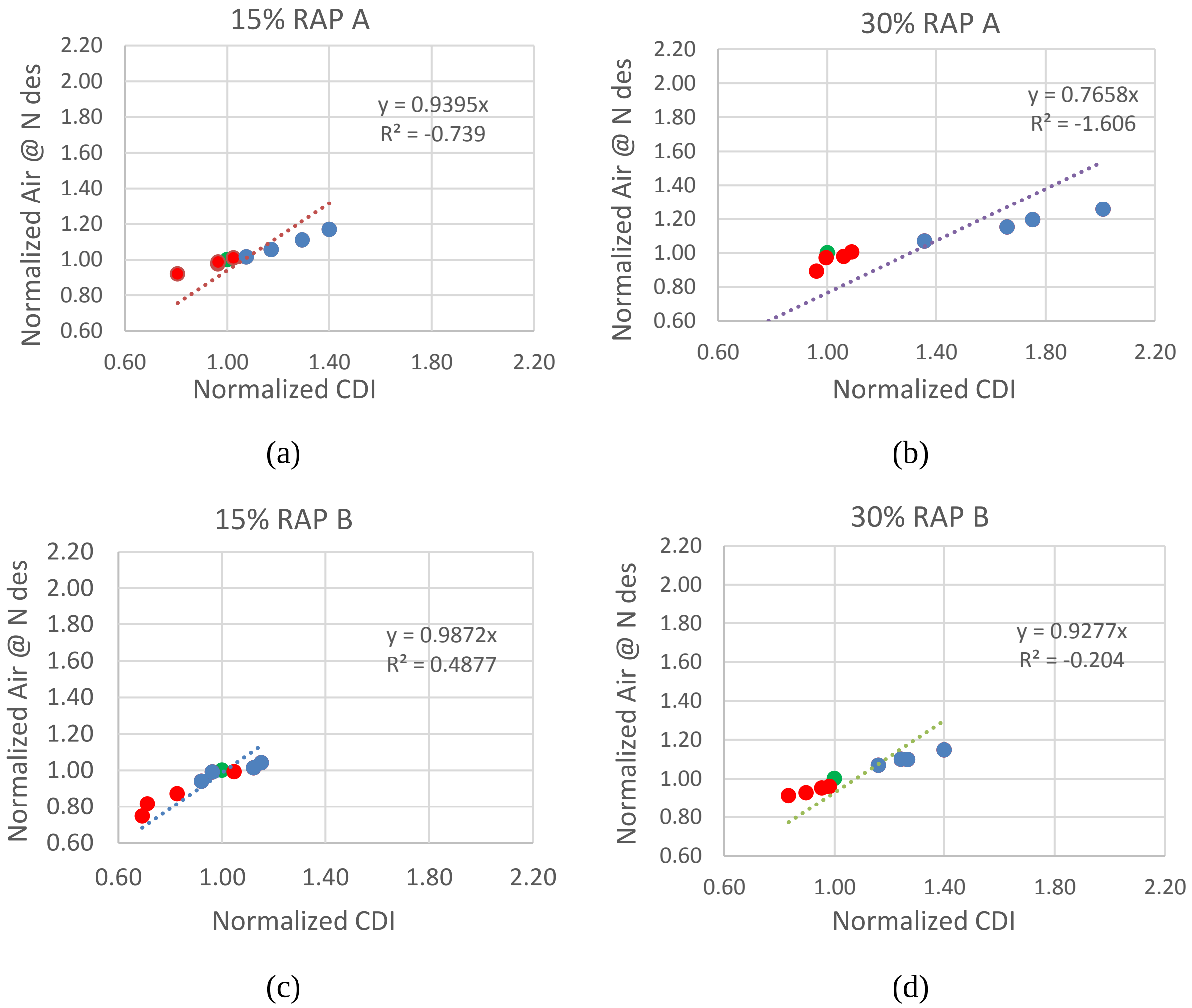
Figure 19 - Change in air content with RAP contnet and production temperatures.

In Figure 19, all mixes are exposed to the same compaction energy (N_{des}). The aggregate structure is maintained constant when the RAP content is changed from 15% to 30%. The only variations are the binder contributions and the temperature. It can be noticed that the control mix (No WMA, HMA temperature) achieved the target air content. The following observations can be made:

1- At 15% RAP + HMA Temperature: The air voids are **on target or lower**. This is regardless of the WMA additive used or the RAP source.
2- At 30% RAP + HMA Temperature: The air voids are **on target or lower**.
3- At 15% RAP + WMA Temperature: The air voids are **on target or higher**.
4- At 30% RAP + WMA Temperature: The air voids are **higher than target.**

It can be clearly seen that the mixes at 30% RAP are harder to compact at WMA temperatures, but when the additive is used as compaction aid at traditional temperatures, compaction becomes feasible. The same effect is captured more clearly by using the densification index, where the Construction Densification Index (CDI) shows the difference in behavior under compaction more distinctly.

Figure 20 (a-d) presents a plot of the normalized CDI values against normalized air contents for the all thirty-two (32) mixes produced in Phase I. the “Red” dots denote the mixes produced at the Hot Mix Asphalt (HMA) temperatures, while the “Blue” dots represent the WMA mixing temperatures. The “Green” dots are the control mixes that were also produced at HMA temperatures. The normalization is achieved by dividing the mixes values by those of the control mixes. Therefore, the control will always have the value of 1.0, mixes requiring more energy to compact will show values above 1.0, and mixes requiring lower energy to compact will have values less than 1.0.



(a) (b)

(c) (d)

Figure 20 - Normalized air content vs. normalized CDI.

Figure 20 shows two (2) interesting points. The 1st is that the CDI values show a greater sensitivity to the changes in compaction compared to the air voids at N_{des}. This is seen in the wider spread of the data in the direction of the x-axis of the plots. The 2nd point is the clear increase in the compaction energy, as captured by the CDI values, for WMA mixes compared to that of the HMA. Further, the densification indices validate the previously mentioned stipulation that the WMA additives work as effective compaction aids at high RAP and high temperatures. In most mixes, approximately the same level of compaction is achieved with the use of WMA additives, given that the production temperatures are not lowered. The data also show that this behavior is independent of the WMA additive used, or the RAP source.

Therefore, to continue to use RAP at WMA temperature, the DOT needs to revise the current state of practice when higher RAP content is used with WMA. The revisions could include allowing for higher virgin binder in the mix than currently used, or producing mixes and compacting them at higher temperature.

5.2 Phase II Results

In this section, an overview of the results obtained in the cracking resistance evaluation is provided. The Semi Circular Bend (SCB) test was conducted at intermediate temperatures to characterize the performance of the mixes. The results cover the effect of the four (4) factors in relation to the flexibility index, fracture energy, and strength of the sixteen (16) mixes that were tested as part of the cracking resistance study. The results for the four (4) control mixes are also provided to serve as a baseline for comparison.

5.2.1 Flexibility Index (FI)

The flexibility index is calculated by dividing the fracture energy obtained from the SCB test by the resistance to crack propagation as measured by the slop of the post-peak curve at the inflection point. Higher flexibility index values indicate flexible mixes with more ductile failures. There are no standard limits for acceptance for test; however, the Illinois Department of Transportation (IDOT) has adopted a limit tailored for their local mixes. According to IDOT, flexibility index of eight (8) is set as a minimum acceptance limit (IDOT-Circular Letter 2016-25).

The experimental program followed a full factorial design to study the influence of the four (4) significant factors selected from Phase I of this study. These factors are:

A- RAP Content,
B- RAP Source,
C- Production Temperature, and
D- Binder Grade

The full factorial experiment results revealed that the effect of the RAP content is overwhelming the data such that the bias level is too high to conduct full analysis. This can be seen in the normal probability plot presented in Figure 21.

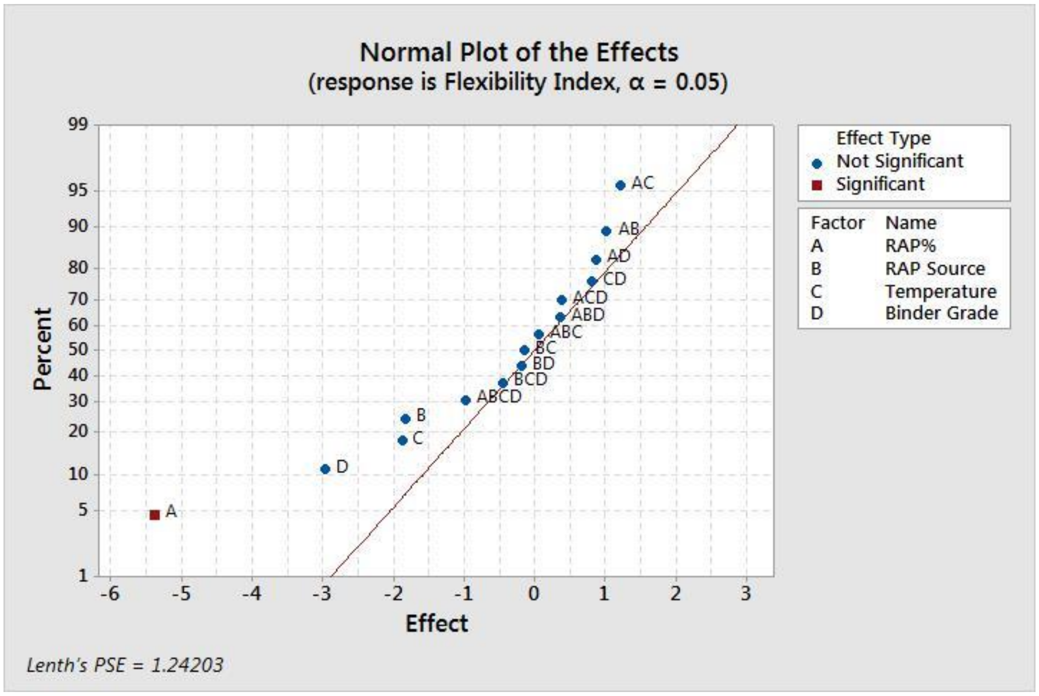


Figure 21 – Normal probability plot of the studied factors (Minitab®).

Further analysis of the data while excluding RAP content to evaluate whether the remaining three (3) factors are statistically significant was conducted. Analysis for variance (ANOVA) is conducted using Minitab® software. The results are shown below.

```
Analysis of Variance

Source          DF   Adj SS   Adj MS  F-Value  P-Value
  Binder Grade   1   35.254  35.2539     3.07    0.105
  RAP Source     1   13.500  13.4995     1.18    0.299
  Temperature    1   14.241  14.2412     1.24    0.287
Error           12  137.739  11.4782
```

Based on the results above, RAP source and production temperature do not influence the flexibility index (P-value of 29.9% and 28.7% respectively). However, the Binder Grade, is border line significant with confidence of 89.5% (P-value =10.5%).

Due to the results obtained from the statistical analysis, the results of the cracking resistance test undergo comparative analysis instead. Figure 22 confirms the results of the statistical analysis with regards to the impact of the RAP content as well as the binder grade on the flexibility index of the produced mixes. It can be seen that the overwhelming majority of the mixes at the lower RAP content of 15% are passing the minimum flexibility index of 8 proposed by the Illinois DOT with the exception of two (2) mixes. These two (2) mixes are discussed in more details in the next figures. On the other hand, all mixes that contain 30% RAP fail the flexibility index limit with the exception of one (1) mix. The mixes that are produced with the softer binder (PG 58-22) have higher flexibility index values than those produced with the PG 64-22 binder, which includes the control samples. However, the effect of the softer binder is not sufficient to counterbalance the stiffening effect of the higher RAP content. This is seen in the 30% RAP mixes that are produced with the softer binder but still fail the flexibility index limit.

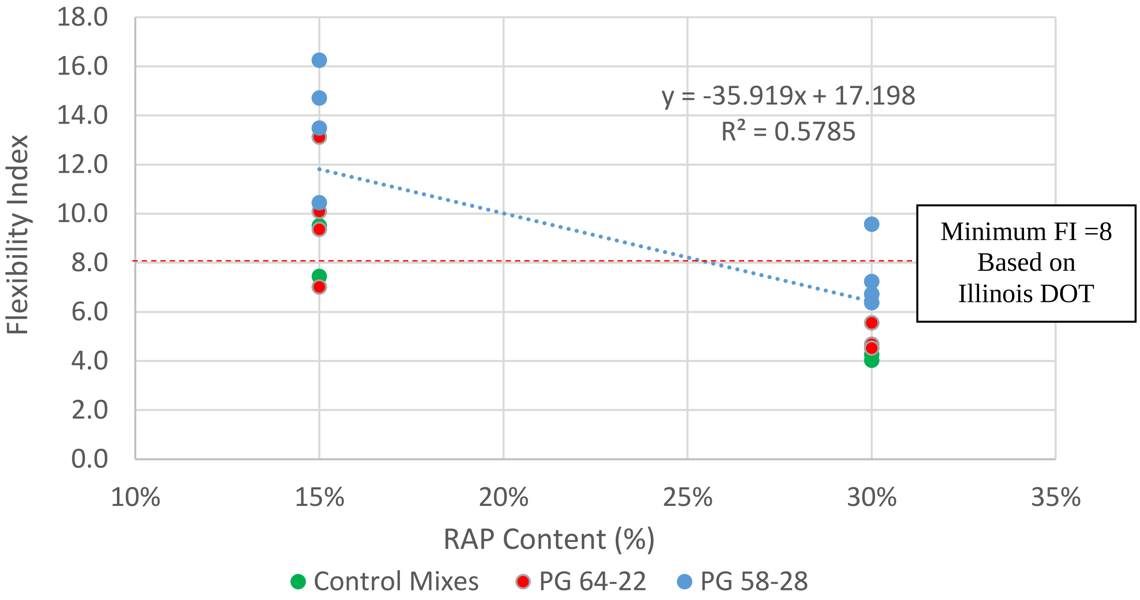
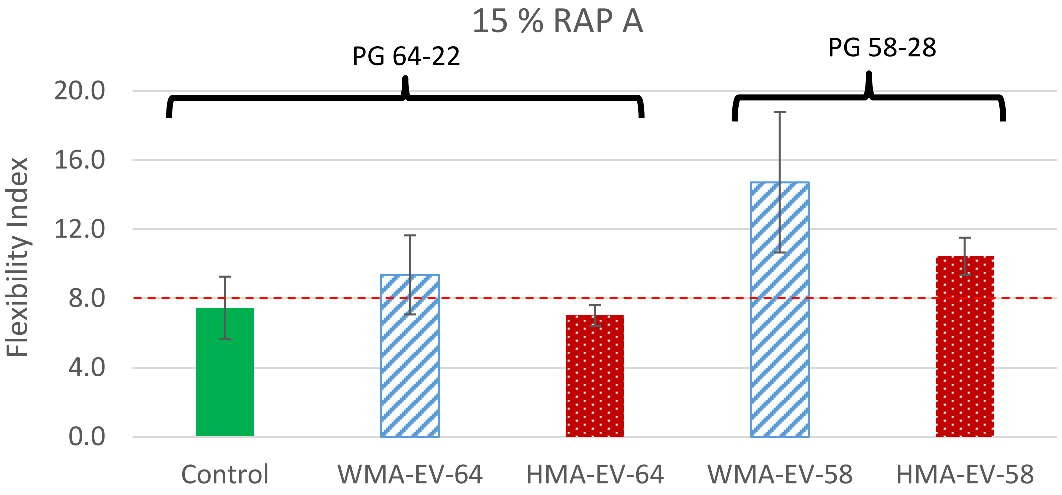


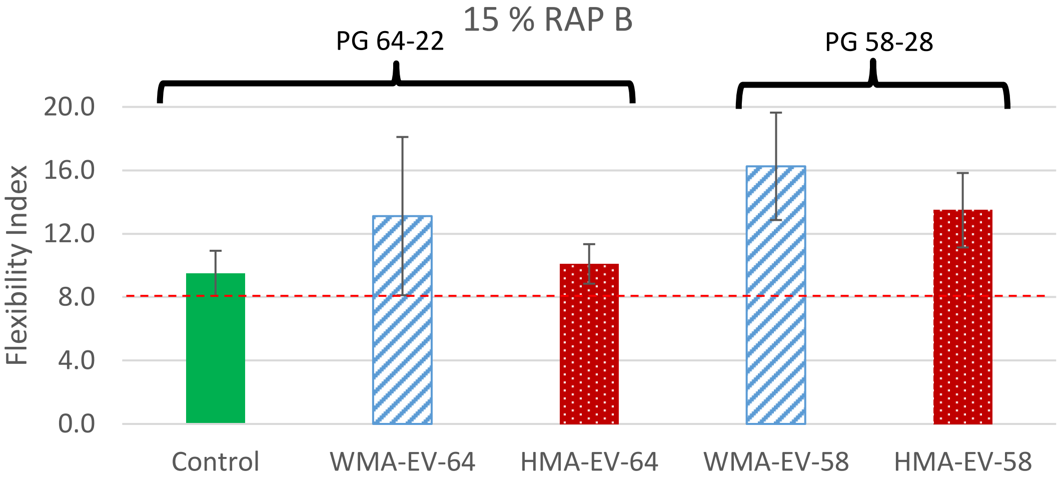
Figure 22 - Change in the flexibility index with RAP content.

Figure 23 presents detailed flexibility index results for all sixteen (16) combinations of mixes, in addition to the four (4) control mixes that are shown on the far left side of the figure. For the 15% RAP mixes, using PG58-28 binder improve the cracking resistance of the mixes. As a general observation, at 15% the error bars overlap for all PG 64 mixes including the control. This indicates that the WMA technology at this level can maintain the mix properties at lower production temperature.

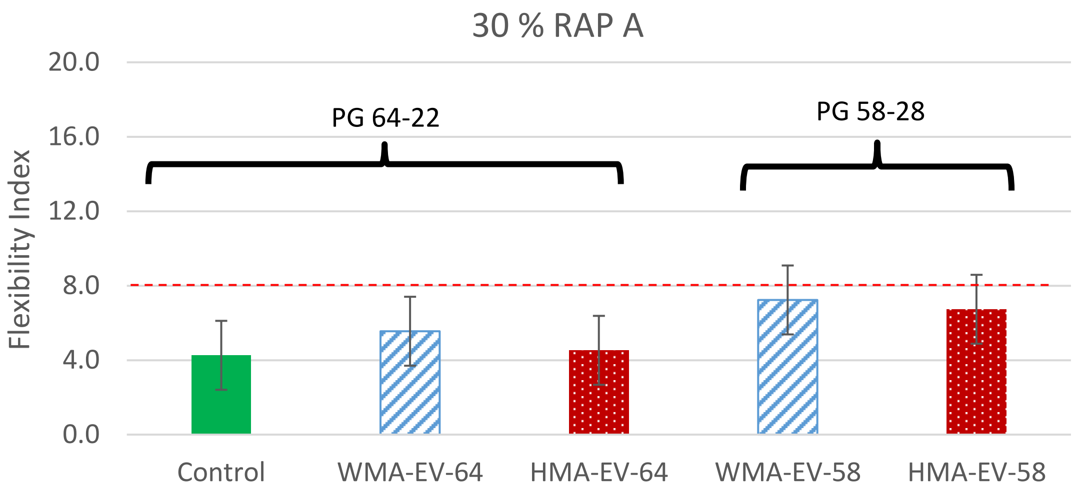
At 30% RAP all the mixes drop below the FI value of 8. The only exception is the combination of 30% RAP B + PG58-28 + WMA production temperature. The SCB testing protocol typically produce high variability between specimens. This is clear as demonstrated by the error bars in Figure 23.


15 % RAP A
PG 64-22
PG 58-28
Flexibility Index
20.0
16.0
12.0
8.0
4.0
0.0
Control
WMA-EV-64
HMA-EV-64
WMA-EV-58
HMA-EV-58

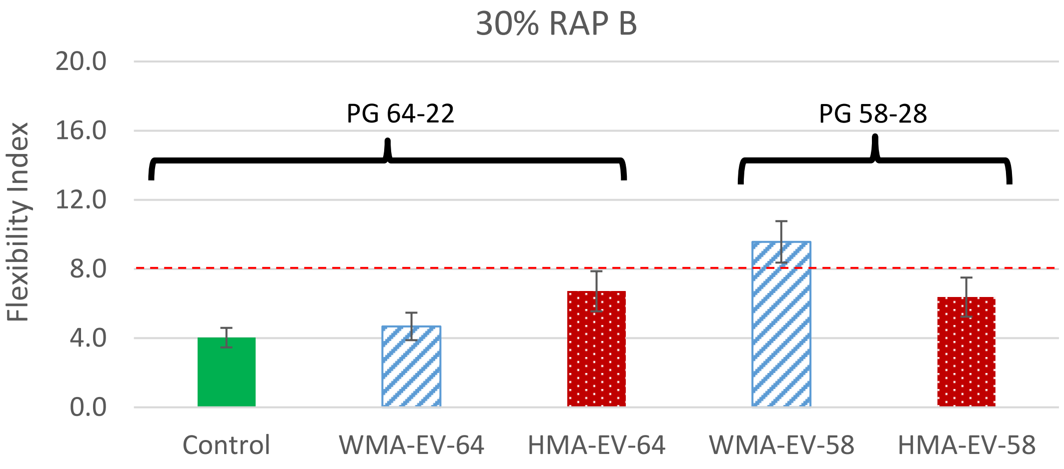
(a)


15 % RAP B
PG 64-22
PG 58-28
Flexibility Index
20.0
16.0
12.0
8.0
4.0
0.0
Control
WMA-EV-64
HMA-EV-64
WMA-EV-58
HMA-EV-58

(b)



(c)



(d)

Figure 23 - Effect of the different factors on the flexibility index.

From figure 23 (c) and (d) it can be observed that at 30% RAP content, even with the use of both the WMA temperatures and a soft binder, the flexibility index remains very low. The mixes that did not pass the FI limit at 15% RAP do not pass the limit if the RAP content is increased to 30% regardless of the use of the softer binder and mixing temperatures. The effect of the RAP content masks the effect of all of the other factors combined.

5.2.2 Fracture Energy

The fracture energy is calculated based on the area under the force-displacement curve, where this area (work of fracture) is divided by the ligament area to obtain the fracture energy. Figure 24 shows the change in the fracture energy with the use of different binder grades. It is seen that the use of the softer binder reduces the fracture energy of the mixes. This a logical trend that is observed in the results. The fracture energy does not show a significant change for the the production temperatures, RAP content, and RAP source. This was also observed by other researchers that reported that the use of the fracture energy alone does not capture the effect of the production variables (Al-Qadi et al 2015, Ling et al 2017).

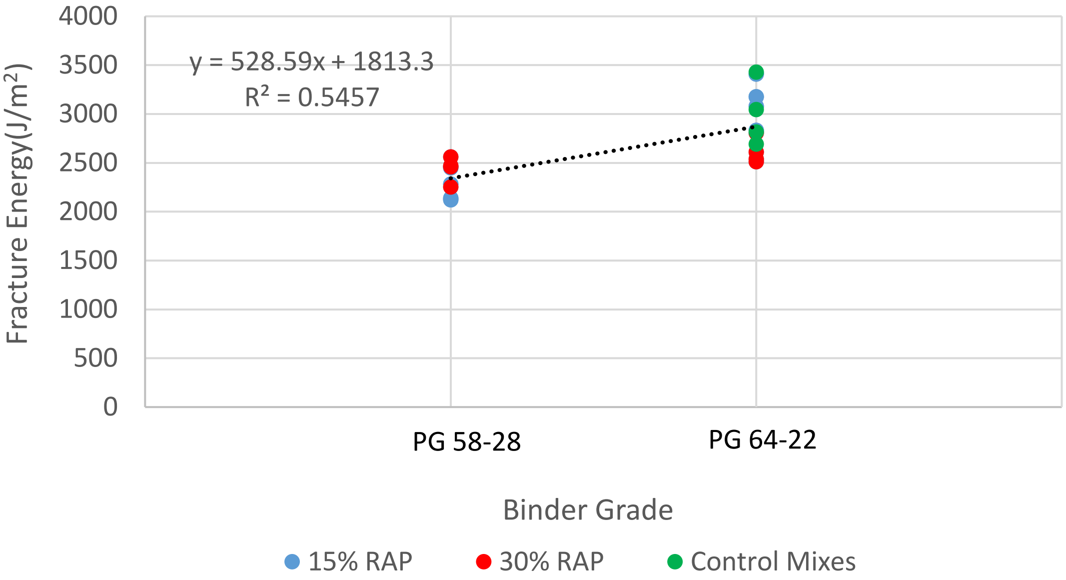
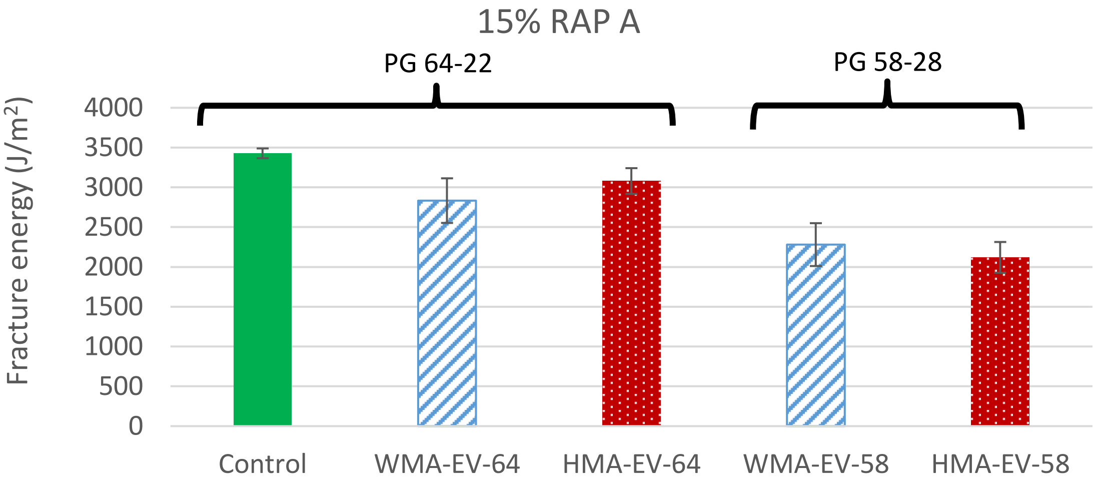
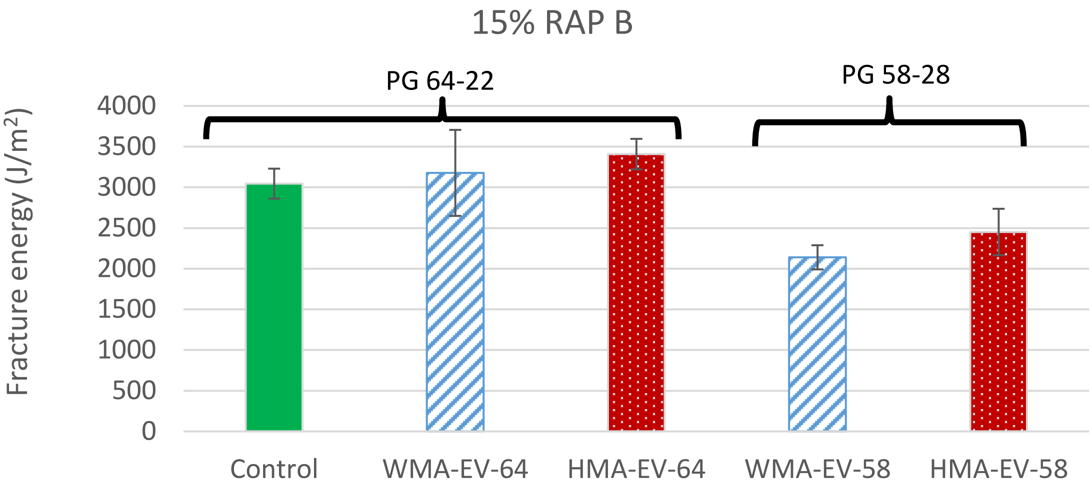


Figure 24 - Change in the fracture energy with binder grade

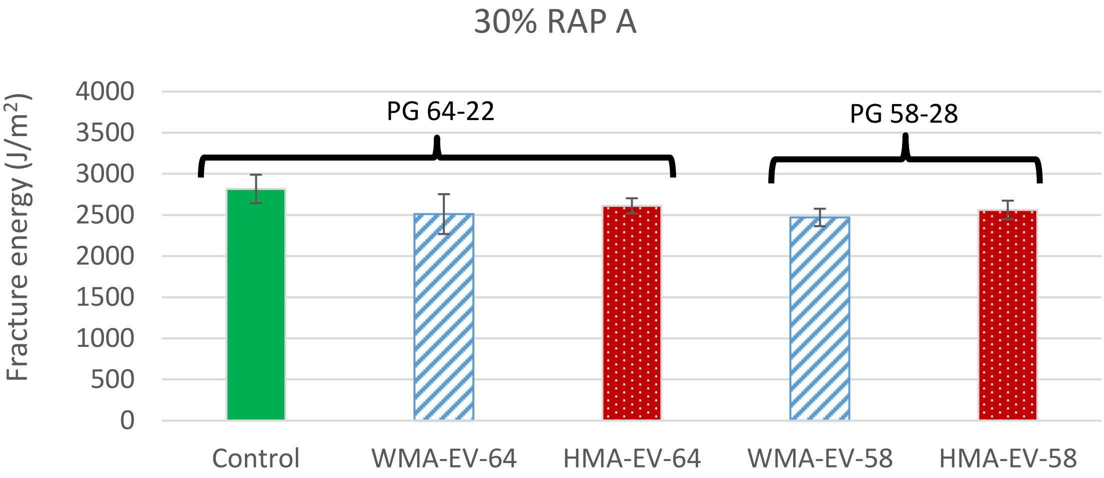
In figure 25 (a-d) the effect of the mixing and compaction temperatures, binder grade and the use of the WMA additive on the fracture energy of the four (4) categories of mixes for the two (2) RAP sources and two (2) RAP contents is shown. The impact of the softer binder on the fracture energy is evident for mixes with 15% RAP mixes. For the 30% RAP mixes, there are barely any difference between the mixes regardless of all other factors.



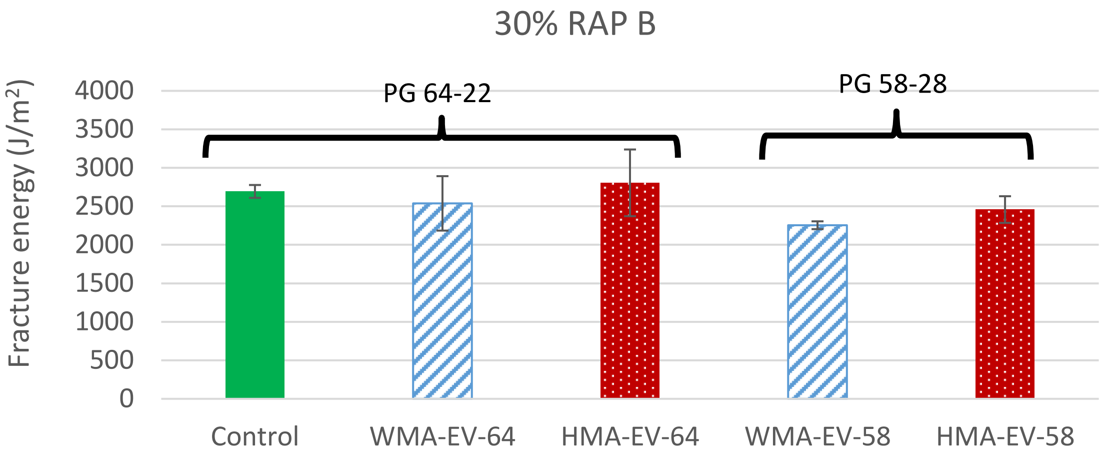
(a)


15% RAP B
PG 64-22
PG 58-28
Fracture energy (J/m2)
4000
3500
3000
2500
2000
1500
1000
500
0
Control
WMA-EV-64
HMA-EV-64
WMA-EV-58
HMA-EV-58

(b)


30% RAP A
PG 64-22
PG 58-28
Fracture energy (J/m2)
4000
3500
3000
2500
2000
1500
1000
500
0
Control
WMA-EV-64
HMA-EV-64
WMA-EV-58
HMA-EV-58

(c)



(d)

Figure 25 - Effect of the different factors on the fracture energy.

5.2.3 Mix Strength

Figure 26 shows the effect of the binder grade on the strength of the studied mixes. As it is expected, the mixes produced with the PG 64-22 binder show higher strength in comparison with those produced with the PG 58-28 binder. The 30% RAP mixes show a higher strength than the 15% RAP mixes. This is also logical, given the stiffer nature of the higher RAP mixes.

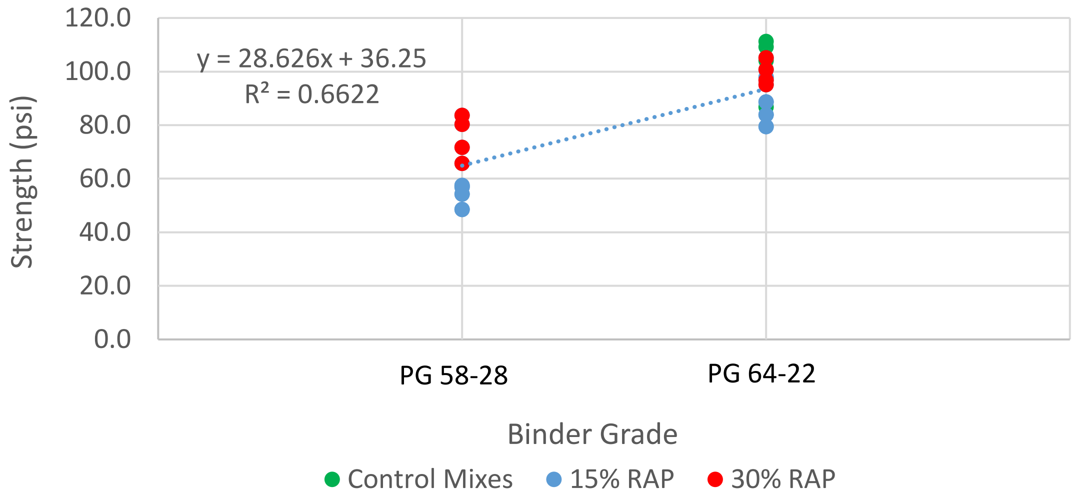
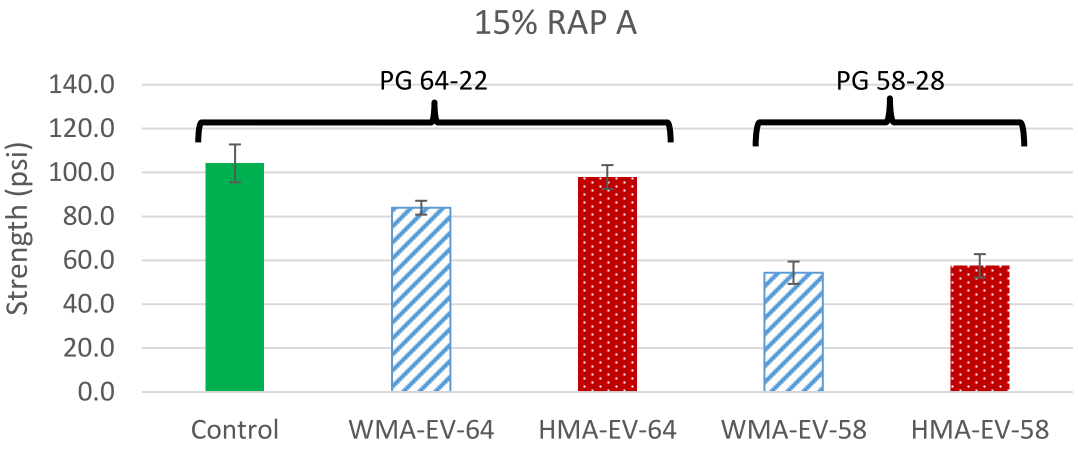
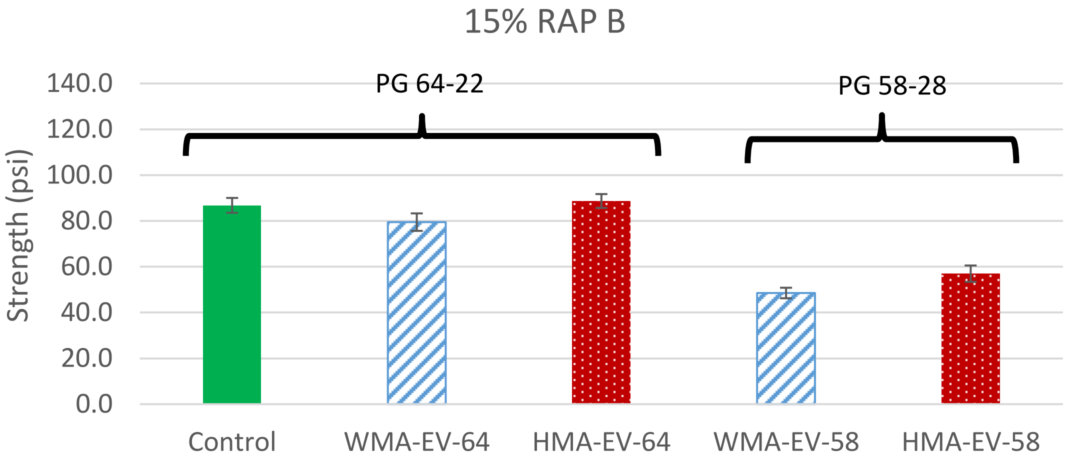


Figure 26 - Change in the strength with the binder grade.

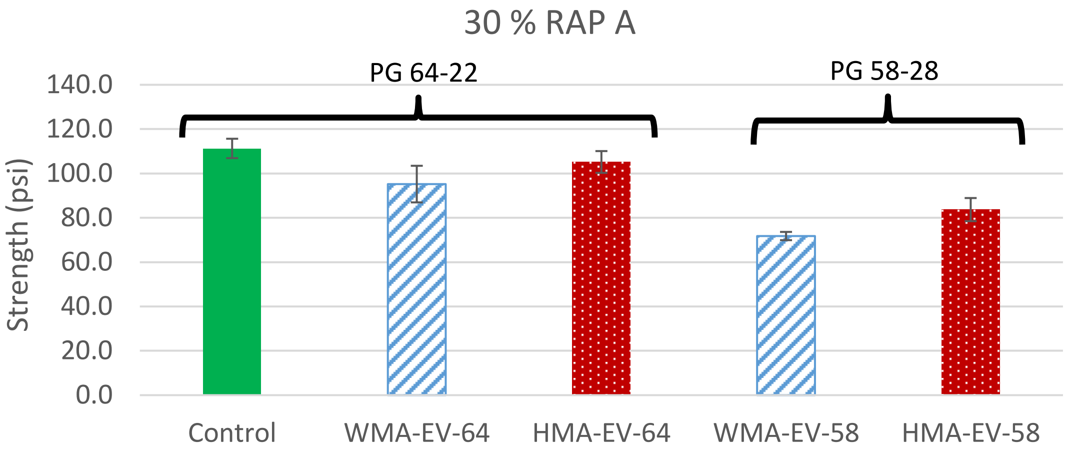
Figure 27 shows the strength results for the mixes including the four (4) control ones. The WMA additive shows no obvious effect on the strength of the mixes. The results show increase sensitivity to the binder grade as the strength of the PG58 mixes are consistently lower across the RAP contents. There no apparent effect of the production temperature on the strength.


15% RAP A
Strength (psi)
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
PG 64-22
PG 58-28
Control
WMA-EV-64
HMA-EV-64
WMA-EV-58
HMA-EV-58

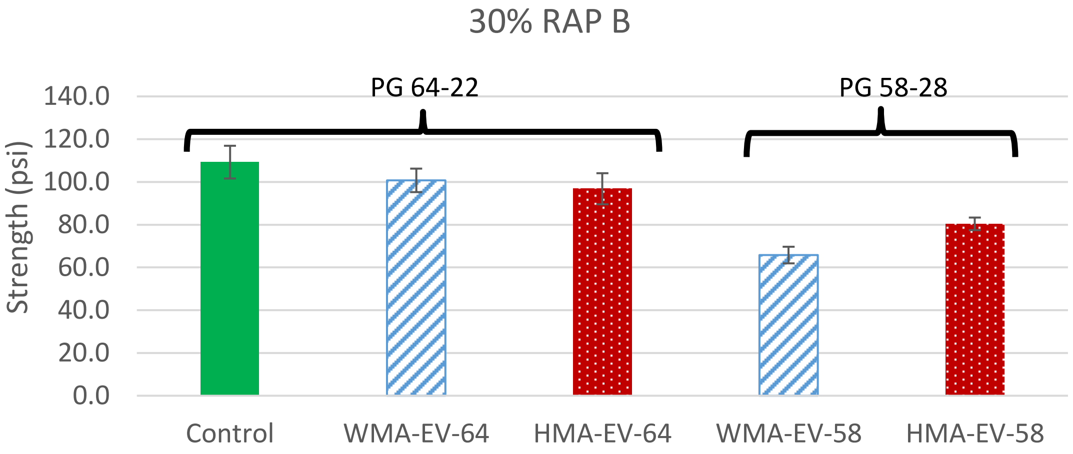
(a)


15% RAP B
Strength (psi)
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
PG 64-22
PG 58-28
Control
WMA-EV-64
HMA-EV-64
WMA-EV-58
HMA-EV-58

(b)



(c)



(d)

Figure 27 - Effect of the different factors on the mix strength.

6 RECOMMENDATIONS FOR PENNDOT:

The current specifications for production of WMA mixes adopted by PennDOT (Pub. 408) mainly focuses on the production temperatures of the mixtures with regards to the achievement of the required volumetric properties, as is the case with the conventional HMA mixes. However, the current method of mix evaluation overlooks the effect of the WMA production conditions at higher RAP content on the cracking performance of the mixtures. This can risk increased compaction effort or production of mixtures that are prone to premature cracking failures, especially in the cases where high concentrations of RAP materials are incorporated into the WMA mixes. The use of WMA as compaction aid to achieve volumetric goals is not sufficient to avoid potential cracking in the field.

The results obtained from the Semi-Circular Bend (SCB) crack resistance testing in this project showed the overwhelming effect of the RAP content in reducing the flexibility index of the mixes. The results indicate that the negative effect of the RAP content may be mitigated through changing the binder grade, increasing binder content, or changing the WMA additive dosage. To quantify these changes further testing is recommended.

Without studying these changes, relying on the current specifications in PennDOT Pub 408 Table A (shown in Table 6 below) must be amended to include performance related testing. This necessitates development of restrictions that would help identify high-RAP WMA mixes that maybe prone to premature failures or early age cracking. It is imperative that the production conditions of such mixes are modified to insure achievement of volumetric requirements as well as satisfactory performance.

Table 6 – Production temperature ranges for WMA mixtures (Adopted from PennDOT Pub. 408)

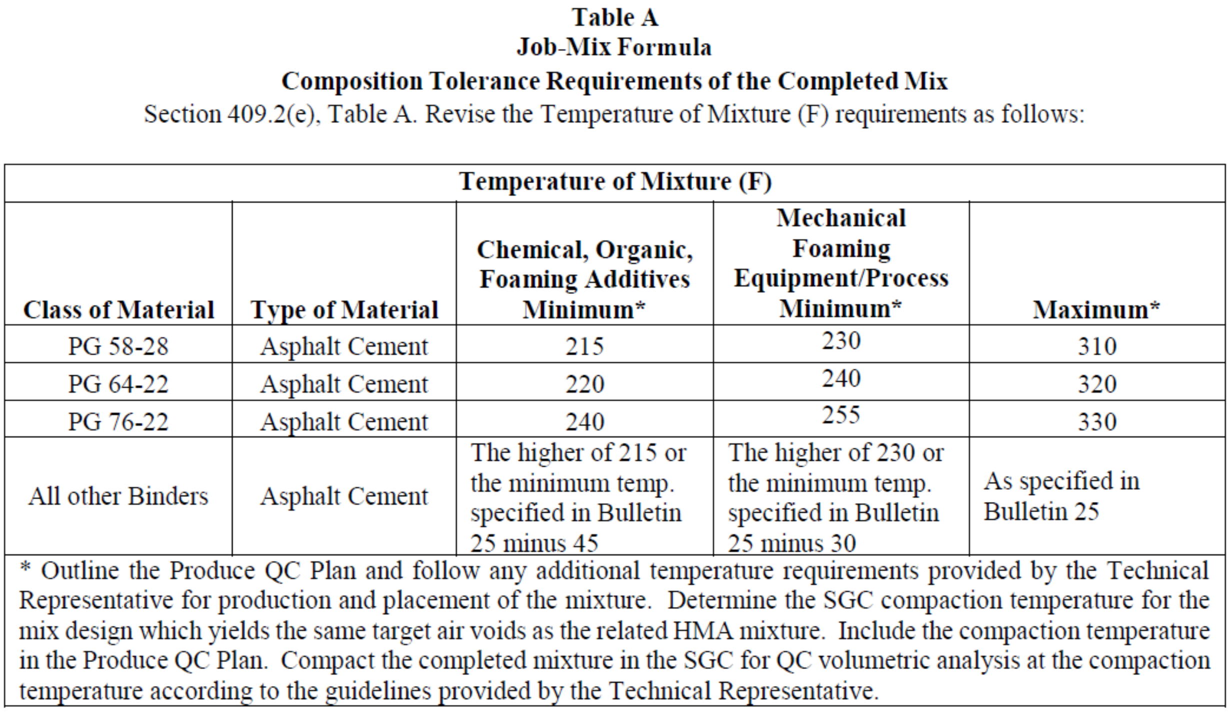


Table A
Job-Mix Formula
Composition Tolerance Requirements of the Completed Mix

Section 409.2(e), Table A. Revise the Temperature of Mixture (F) requirements as follows:

Temperature of Mixture (F)				
Class of Material	**Type of Material**	**Chemical, Organic, Foaming Additives Minimum***	**Mechanical Foaming Equipment/Process Minimum***	**Maximum***
PG 58-28	Asphalt Cement	215	230	310
PG 64-22	Asphalt Cement	220	240	320
PG 76-22	Asphalt Cement	240	255	330
All other Binders	Asphalt Cement	The higher of 215 or the minimum temp. specified in Bulletin 25 minus 45	The higher of 230 or the minimum temp. specified in Bulletin 25 minus 30	As specified in Bulletin 25

* Outline the Produce QC Plan and follow any additional temperature requirements provided by the Technical Representative for production and placement of the mixture. Determine the SGC compaction temperature for the mix design which yields the same target air voids as the related HMA mixture. Include the compaction temperature in the Produce QC Plan. Compact the completed mixture in the SGC for QC volumetric analysis at the compaction temperature according to the guidelines provided by the Technical Representative.

Such recommendations can be achieved through the following steps:

1- Conduct performance testing on mixes known to perform well in the field. Compare their performance to other mixes showing premature cracking.
2- Establish performance limits for screening high risk mixes.
3- Adapt the current specifications to high RAP WMA mixes production to assume proper compaction during construction.
4- Identify feasible path to address proper compaction. This can be through changes in binder grade, production temperature, or WMA additive dosage.

7 SUMMARY AND CONCLUSIONS

In this study, six (6) factors of importance in the production of RAP-WMA mixes were identified and evaluated in terms of the significance of their effect on the workability, mechanical stability and performance of RAP-WMA mixes. The factors included mixing/compaction temperatures, RAP content, RAP source, WMA additive type, binder grade, and conditioning time. A two (2) phase experimental program was designed for the evaluation of the abovementioned factors. Phase I of the study examined the influence of these factors on the volumetric properties, workability, and mechanical stability of RAP-WMA mixes. Phase II examined the performance of the RAP-WMA mixes by studying the fracture resistance of the produced mixes with the use of the Semi-Circular Bend (SCB) test. The following conclusions were reached:

1. Mixing and compaction temperature have a significant effect on the volumetric properties, and workability of WMA mixes at higher RAP content.
2. RAP source and RAP content are significant factors controlling the ability to produce asphalt mixtures meeting the PennDOT mix design requirements.
3. For the WMA technologies examined in this study, the WMA additive type show similar effect on the mixtures volumetrics and workability. Their effects diminished at 30% RAP content. The effectiveness of the WMA technologies is revived when the 30% RAP mixes are produced at higher temperatures comparable to HMA. This trend can be stipulated to be dependent on the contribution of the RAP binder to the mixture matrix. WMA technologies are not expected to behave as binder extenders but rather as lubricants during compaction allowing for aggregate particles to reorient during compaction. Therefore, at higher RAP content, unless the RAP binder contributes to the matrix, the aggregate particles will not have access to this lubricant to promote compaction.
4. The conditioning duration and binder grade exhibit no palpable effect on the workability of high RAP WMA mixes as measured by the CDI and volumetric properties.
5. The Effect of the RAP content is overwhelming the mixes' cracking resistance performance, given that all the mixes were produced with the same aggregate structure. The higher the RAP content the more cracking prone the mixes will be. This trend logical given the reduction in the virgin binder in the mix at higher RAP content. The dosage of the WMA technology should be a function of the RAP content. This research did not study the effect of the WMA dosage on performance of high RAP content mixes. The results of the SCB clearly show that the WMA additives used are not able to mitigate the effect of the higher RAP content. This raises important questions as to how high RAP content can be employed without sacrificing the performance.
6. The results of this study reveal that the current mix design protocol does not necessarily guarantee adequate performance in terms of cracking resistance. This study used a single aggregate structure, and an optimum asphalt content to meet the PennDOT volumetric requirements. These mixes performance as measured by the SCB test showed varying performance with changes that did not affect the volumetrics.

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